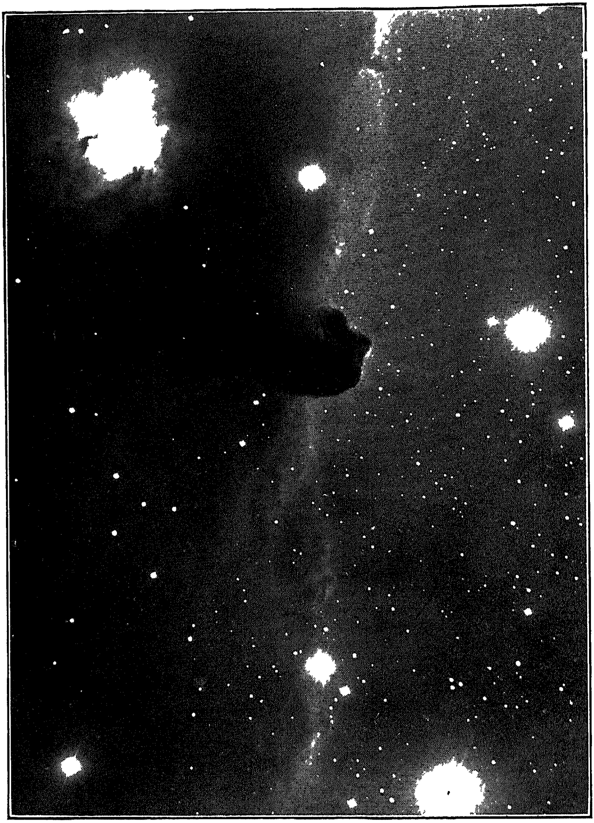
THE DEPTHS OF THE UNIVERSE



Dark nebula in Orion

Photographed by Duncan with the Hooker Telescope

THE DEPTHS OF THE UNIVERSE

BY

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WITH
NUMEROUS ILLUSTRATIONS

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TO

M H H AND W. B H.

IN MEMORY OF

KENWOOD DAYS

PREFACE

THE three chapters of this little book have appeared during the last two years as articles in *Scribner's Magazine*. They relate for the most part to observations and discoveries made at Mount Wilson, and thus continue the series begun in "The New Heavens" Although briefly summarized in that volume in the chapter on "Cosmic Crucibles," the evidence proving the existence of magnetic fields in sun-spots is given more fully here, as an essential part of the deduction of the law of sun-spot polarity

I am indebted for the illustrations chiefly to the present and former members of the staff of the Mount Wilson Observatory whose names appear in the text, to the late Professor Barnard and the Yerkes Observatory, to E Walter Maunder, Esq , and the Royal Astronomical Society, to the Royal Institution, and to Messrs. Houghton, Mifflin & Co for permission to copy one of Langley's sun-spot drawings from his book, "The New Astronomy."

G E. H

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THE DEPTHS OF THE UNIVERSE

> "Below lay stretched the boundless universe!
> There, far as the remotest line
> That limits swift imagination's flight,
> Unending orbs mingled in mazy motion,
> Immutably fulfilling
> Eternal Nature's law
> Above, below, around,
> The circling systems formed
> A wilderness of harmony—
> Each with undeviating aim
> In eloquent silence through the depths of space
> Pursued its wondrous way"
>
> —SHELLEY, "The Dæmon of the World"

ON the night of the 7th of January, in the year 1610, Galileo first directed his telescope toward Jupiter In doing so he literally took his life in his hands Ten years earlier Giordano Bruno, disciple and public expositor of Copernicus, had been burned at the stake in Rome The agents of the Inquisition, with unrelaxed vigilance, still watched eagerly for new victims among those who ventured to question their doctrines. Galileo had already taught the Copernican theory, he was soon to demonstrate it beyond room for doubt. The pages from his note-books which reveal the successive steps of his great discoveries are among the chief documents that mark the turning-point from mediæval to modern thought

Jupiter was shown by the telescope to be accompanied by three unknown stars, two to the east and one to the west. The mere detection of unfamiliar fixed stars no longer surprised Galileo, as his telescopes had multiplied such objects a hundredfold. But their arrangement in a nearly straight line, parallel to the ecliptic, struck his attention. The next evening, chancing to look at Jupiter again, he was astonished to find that the three stars, still in a straight line, were all to the west of the planet. This impressed him deeply, as the motion of Jupiter, at that time direct instead of retrograde, should have produced an apparent displacement of fixed objects in the opposite direction. The next night, much to his disgust, the heavens were covered by clouds. On January 10 only two stars were seen, both to the east of the planet. The third, he suspected, might be concealed by its disk. Then the truth, of which some glimmerings had perhaps reached him before, slowly began to dawn. Jupiter's own motion could not account for such displacements of his companions. These must be smaller planets circulating about him! Thus, Jupiter would resemble the sun of Copernicus, set in the centre of a miniature solar system. Here was a new and splendid conception, but observation alone must decide.

Thus for sixty-six nights, as the original manuscript pages still show, Galileo pursued his study of the system of Jupiter. On the 13th of January, he saw four companion stars, visible again the next

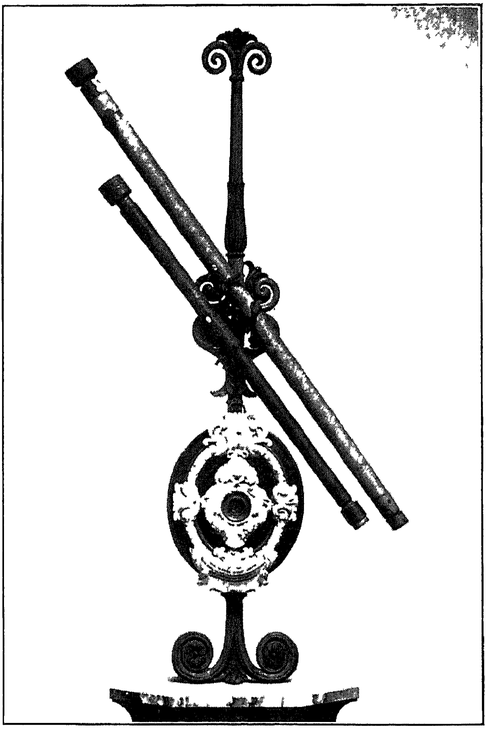


Fig. 1. Two of Galileo's telescopes, preserved in the Tribuna di Galileo at Florence

A broken object-glass, with which the four satellites of Jupiter were discovered, is mounted in the centre of the ivory frame

night The true significance of his observations then appeared

"It is now," he says in conclusion, "not simply a case of one body (the moon) revolving around another body (the earth), while the two together make a revolution around the sun, as the Copernican doctrine teaches, but we have the case of four bodies or moons revolving round the planet Jupiter, as the moon does round the earth, while they all with Jupiter perform a grand revolution round the sun in a dozen years"

The striking appearance of this miniature solar system, soon supported by Galileo's discovery of the changing phases of Venus, broke down the opponents of Copernicus and gradually led to the acceptance of his theory Thinking men were forced to admit that the sun, not the earth, lies at the centre of our system But the church, stiffened in its opposition, condemned and placed on the Index "this false Pythagorean doctrine, contrary to Holy Scripture, of the mobility of the earth and the immobility of the sun, taught by Nicolas Copernicus" —and in 1633, under threat of torture, Galileo, old and broken, was forced to retract his teachings

Fortunately for human progress, no law of man can overthrow the truths of nature, though the history of the Middle Ages shows that their acceptance can be retarded for centuries The contribution of Galileo was not merely an intellectual feat, a delight to the *cognoscenti* it was literally a revolution in human thought

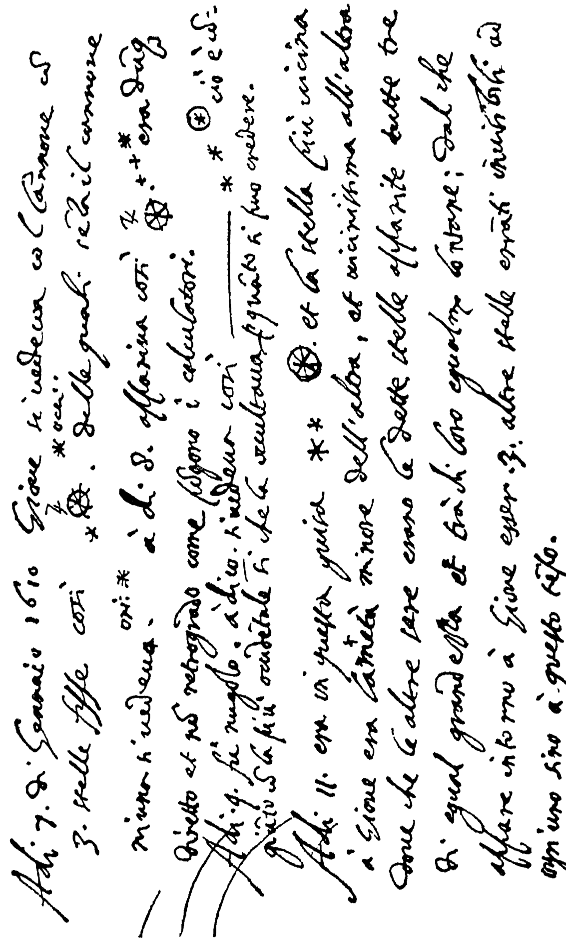


Fig 2 Part of Galileo's manuscript, recording his first observations of the satellites of Jupiter

MEDIÆVAL MINDS

When Copernicus, years before Galileo's discovery, presented his arguments against the geocentric system, they were received with universal

Fig 3 Milton visiting the Blind Galileo
Painted by Tito-Lessi

scorn Church and school men were wedded to the past, and Oxford had decreed that "Masters and Bachelors who did not follow Aristotle faithfully were liable to a fine of five shillings for every point of divergence, and for every fault committed against the logic of the Organon" When Scheiner, the rival of Galileo, informed the provincial of his order

of his observation of sun-spots, this worthy remarked "I have read Aristotle's writings from end to end many times, and I can assure you I have nowhere found anything similar to what you describe. Go, my son, and tranquillize yourself, be assured that what you take for spots on the sun are the faults of your glasses or of your eyes" Writing to Prince Cesi in 1612, Galileo said: "I suspect that this new discovery (of sun-spots) will be the signal for the funeral, or rather for the last judgment, of the pseudo-philosophy—the funereal signals having already been shown in the moon, the Medicean stars (Jupiter's satellites), Saturn, and Venus And I expect now to see the peripatetics put forth some grand effort to maintain the immutability of the heavens!" *

True to his words, he was bitterly attacked on all sides, and soon afterward denounced by the Holy Inquisition

It would be interesting and profitable to recall the extraordinary characteristics of the mediæval mind, which tested everything new by a comparison of ancient texts, and refused to appeal to the simple and direct proof of observation or experiment Luther and Melancthon, among other leaders of human thought, vigorously opposed the Copernican theory, the latter on the ground that "the Holy

* For the above and other pertinent illustrations of mediæval methods see Fahie's interesting "Galileo, His Life and Work" The full details of Galileo's life, with many reproductions of his manuscripts and drawings, are given in Favaro's great national edition of his writings, published by the Italian Government

Scriptures state that Joshua bade the sun stand still and not the earth" But, as Pritchett has pointed out, perhaps the most remarkable evidence of man's persistent dislike of the conception of a

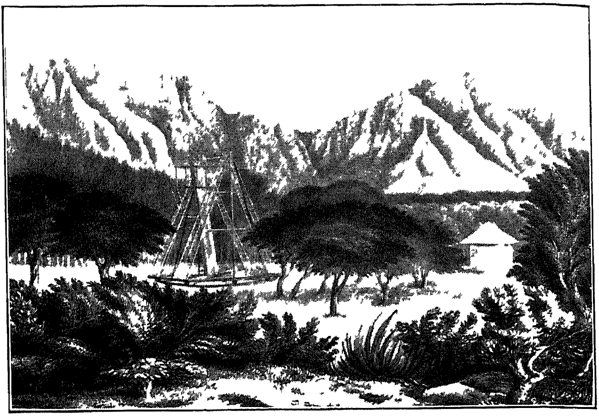


Fig 4 Sir William Herschel's 18-inch telescope, with which he made his studies of the structure of the universe Shown at the Cape of Good Hope, where Sir John Herschel extended his father's work to the southern heavens He estimated that this telescope would show about five and one-half million stars in the entire sky

moving earth is afforded by the strong dissent of Francis Bacon, though truly regarded as one of the founders of modern thought In providing the evidence which ultimately rescued the world from this deplorable state, Galileo initiated the development of modern science and stimulated the discoveries of the explorers and investigators of the Renaissance

Once more, as in the early Greek period and again in the Alexandrian School, astronomy led the way, and by its great discoveries encouraged research in all other branches of science.

Copernicus was not the first to assert the heliocentric hypothesis. Aristarchus of Samos, about 250 B. C., maintained the central position of the sun and, like Galileo, was therefore accused of impiety. Thus man has insisted on personal supremacy from the earliest times. To enforce the central and controlling position of the earth, he did not hesitate to make the sun and planets subsidiary to it. In fact, he required the entire stellar universe to revolve around the earth—a demand which even to the cardinals of the Inquisition might have seemed preposterous if viewed in the light of a little knowledge and a little reason. But their minds were closed, and no conclusions of science could penetrate them. Fortunately their successors have been more enlightened and many astronomical observatories are conducting valuable researches under their auspices.

THE DISTANCE OF THE STARS

Long after Galileo's time, indeed until the closing years of the eighteenth century, the problem of the stellar universe had never been attacked. However, as we have shown elsewhere,* the telescope had steadily grown in aperture and power, until Herschel, with his 18-inch reflector, could count in

* "The New Heavens," Charles Scribner's Sons, 1922.

both hemispheres some five or six million stars By his method of star-gauging he endeavored to determine the structure of the sidereal system, and actually succeeded in reaching a fair conception of its flattened or watch-shaped form But try as he might, he was utterly unable to measure the distance

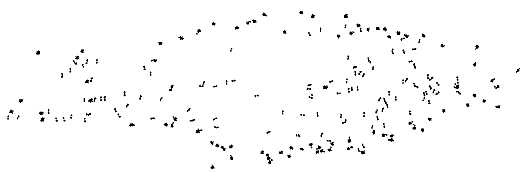


Fig 5 Herschel's cross-section of the stellar universe
The place of the sun is indicated not far from the centre

of even the nearest of the stars The one obvious method of measuring stellar distances, when tested with inadequate instruments, had invariably failed Indeed, if the annual parallax of the stars could have been detected at the time of Ptolemy, the fiction of an immovable earth, with sun, planets, and stars revolving around it, might not have dominated human thought for more than two thousand years

Sit before a window, fix your attention on some speck on the glass, and mark its position against a building on the opposite side of the street Then move your head to the right or left, parallel to the glass, and note the displacement of the speck on the opposite building Step farther away from the window, and repeat the process The displacement of the speck becomes smaller Thus at a sufficient

distance from the window the speck would appear fixed, even when seen from two points a considerable distance apart

Substitute a star for the speck on the glass, and imagine it viewed against a background of very distant stars from two points 186,000,000 miles apart—the diameter of the earth's orbit It is plain that the star must be very remote if it shows no shift when observed from the ends of such an enormous base-line. But prior to the nineteenth century, even with the aid of the most powerful telescopes and the best devices for measurement, no shift of any star's position could be thus detected

Herschel himself used his utmost efforts to apply this method In his sweeps of the heavens he had catalogued many very close pairs of stars, in some of which one member appeared much brighter than the other Assuming the faintness of the lesser star to be caused by its much greater distance, he tried to detect the parallax of the brighter one by careful micrometric measures, made six months apart, of its distance from its faint companion No evidence of a semi-annual shift was detected, but an important advance nevertheless resulted For Herschel found that in many of these pairs one star was apparently revolving about the other Thus were discovered those extraordinary systems, in which two stars, comparable with the sun in diameter and sometimes surpassing it, revolve about their common centre of gravity Millions of such stellar pairs exist, differing greatly from our solar

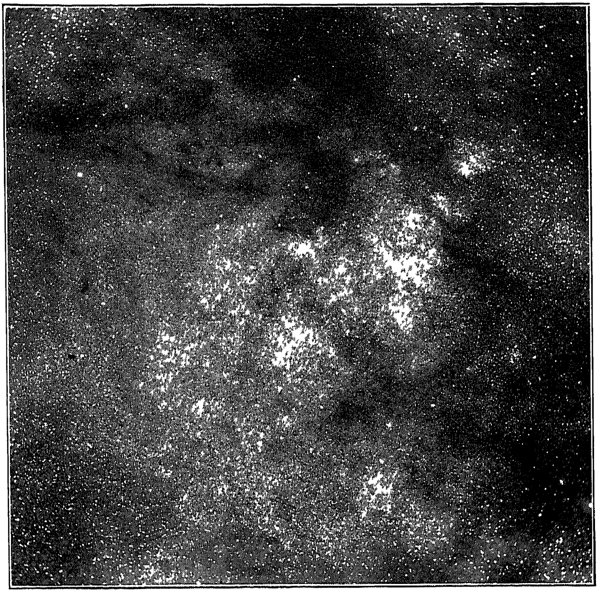


Fig 6 Barnard's photograph of great star clouds in the constellation of the Shield (Scutum)

The cluster Messier 11 is just above the middle of the picture

system, in which the sun is the one luminous and all-dominating body, incomparably greater than the many planets, which revolve about him like little satellites.

HERSCHEL'S EXPEDIENT

Determined as he was to discover the structure of the universe, and unable, because of their remoteness, to measure the distances of the stars directly,

Herschel was forced to adopt a different expedient Consider some brilliant star, such as Vega Its brightness to the eye must depend upon two things: the total amount of light it radiates (its absolute brightness) and its distance from the earth Imagine Vega to retreat into space, until it reaches a point ten times its present distance from us Instead of appearing as one of the brightest stars of the heavens, it would then be barely visible to the naked eye. Suppose it to move still farther away, where it could be followed only with a telescope At 900 times its present distance, according to Herschel's estimate, it could still be seen with his most powerful instrument

Thus if all the stars were of the same absolute brightness, their relative distances could be determined by measuring their apparent brightness. We now know that stars differ enormously in size and in brightness, and Herschel himself did not assume them to be all alike What he did assume was that by dealing with very large numbers of stars, using averages for hundreds or thousands instead of single values, his results would come close to the truth And in this he was not far wrong His picture of the stellar universe, based upon soundings made in every direction, is not very different from that of the present day, though he was, of course, unable to penetrate into the remote depths since rendered accessible by great modern telescopes and the photographic plate He concluded that our stellar system is like a flattened or watch-shaped disk, extending

in the direction of the star clouds of the Milky Way over 900 times the average distance of a first-magnitude star, and less than one-fifth of this distance in

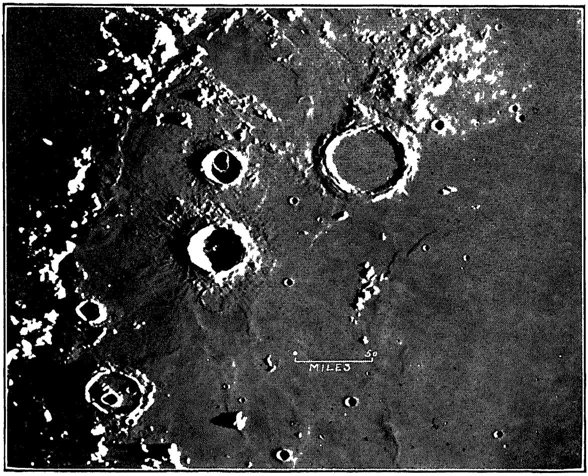


Fig 7 Lunar craters Archimedes, Aristillus, and Autolycus (Pease)

As the scale indicates, the diameter of Archimedes is about fifty miles The sun is on the right, so that the crater walls and mountain peaks cast black shadows to the left

the direction at right-angles But he had no means of determining the average distance of a first-magnitude star In fact, so great is the variation in absolute stellar brightness that certain very faint stars are actually much nearer than some of the brightest ones

This became evident in 1838 when Bessel finally succeeded, by the most refined instrumental means

then available, in measuring the parallax of the star called 61 Cygni, which is barely visible to the naked eye Its displacement, when observed from opposite ends of the earth's orbit, is four-tenths of a second of arc—the diameter of a one-inch ball at a distance of eight miles This means that 61 Cygni is about 40,000,000,000,000 miles from the earth, and affords a first glimpse of the enormous scale of the stellar universe For this is one of the nearest of the stars

SCALE OF THE UNIVERSE

In the light of this result and of late measures of stellar parallaxes, let us see where we stand in our survey of the universe. We must first form some conception of scale if we are to appreciate in any degree the stupendous distances involved Even the earth seems a fairly large body, when we remember that its entire surface has not yet been explored, and reflect, for example, on our impression of the remoteness and peril of expeditions seeking the Pole Yet its diameter is only 8,000 miles Place the earth beside the sun, which is more than 100 times greater in diameter, and it becomes a very insignificant object, much smaller than the larger sun-spots or the enormous flames of glowing gas that rise from the sun's surface The mile is still a practicable unit of measurement, however, and we may even retain it in describing the great distance from the earth to the sun, 93,000,000 miles Neptune, at the outermost limit of the solar system, is 2,800,000,000 miles

from the sun But the moment we pass to the stars no ordinary unit of measurement is large enough for satisfactory use

We therefore substitute the light-year, nearly six million million miles Light travelling at the rate

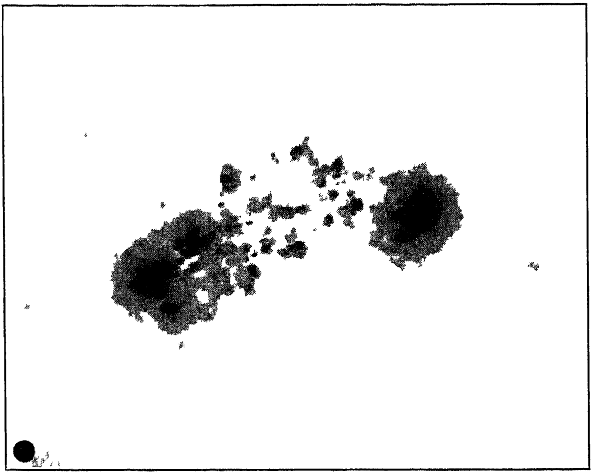


Fig 8 Great sun-spot group, February 8, 1917 (Campbell)
The comparative size of the earth is shown by the disk in the corner

of 186,000 miles per second would pass around the earth in less than an eighth of a second, it reaches us from the moon, our nearest celestial neighbor, in 1 2 seconds, and in about 8 minutes from the sun Alpha Centauri, the nearest of the stars, is $4\frac{1}{3}$ light-years distant Sirius, 26 times as bright as the sun, is 8 7 light-years away Only four stars, in fact, are

known to be less than 10 light years from us Procyon's distance is 11 light-years, while that of Altair is about 15 light-years Vega and Arcturus, each

Fig 9 The Pleiades (Barnard)

The distance from the earth of this well-known cluster of stars, enmeshed in nebulosity, is about 325 light-years

about 60 times as bright as the sun, are about 30 light-years away The spectroscopic binary star Capella, each of whose components is about 100 times as bright as the sun, is 54 light-years distant. Rigel, about 13,000 times as bright as the sun, is

almost 500 light-years from the earth The well-known cluster of the Hyades is at a distance of about 130 light-years, while the Pleiades, a cluster of from 300 to 500 stars, over 30 light-years in diameter, is about 325 light-years away from us The group of blue stars in Orion is nearly twice as remote (600 light-years) Thus we may begin to appreciate the meaning of Herschel's expression that the telescope penetrates into time as well as into space When a new star suddenly blazes out in the Milky Way, and passes rapidly through its changes of light, we are watching events that transpired hundreds of years ago.

SPACE-PENETRATING POWER

Great as these distances are, the objects thus far mentioned must actually be looked upon as our near neighbors in space Beyond them the stars stretch away in countless numbers and decreasing apparent brightness into enormously greater depths As our telescopes increase in size we penetrate farther and farther into these remote depths, and thus bring to view hundreds of millions of stars beyond the range of previous instruments

Look, for example, at the region in Auriga illustrated in Fig. 10 The bright star shown is of magnitude 3 3, and is thus visible to the naked eye No other star appears, though the exposure was long enough to include stars of the ninth magnitude The next step (Fig 11) takes us to the twelfth magnitude, beyond the limit of Galileo's telescopes. Fig

12 includes all of the stars within the reach of Herschel's 18-inch reflector, which attained the fifteenth magnitude The next photograph (Fig 13) includes much fainter stars, while Fig. 14 shows stars down

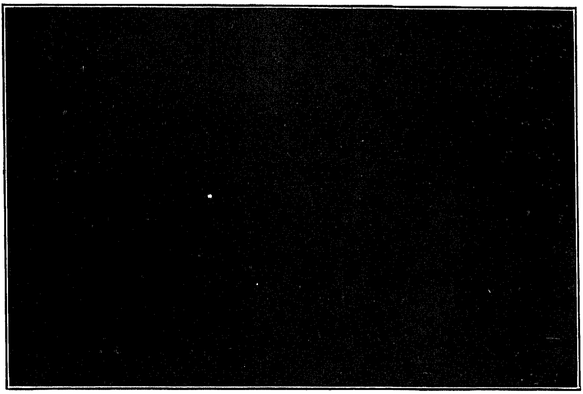


Fig 10 Star field in Auriga (Seares)

Only one star appears, though the exposure was sufficient to show stars to the ninth magnitude

to the eighteenth magnitude All of these pictures were taken by Seares with the 60-inch reflector on Mount Wilson, with increasing exposure times A long exposure with the 100-inch telescope would show many more stars in the same region. Over the whole sky the 60-inch would probably record more than 1,000,000,000 stars, while the 100-inch should add fully 500,000,000 more *

* The larger size of the images of the brighter stars on photographs made with increased exposures is due to a purely photo-

Fig 11 Star field in Auriga

The exposure was long enough to show stars to the twelfth magnitude, beyond the limit of Galileo's telescopes

Fig 12 Star field in Auriga

Showing stars to the fifteenth magnitude, the limit of Herschel's 18-inch telescope

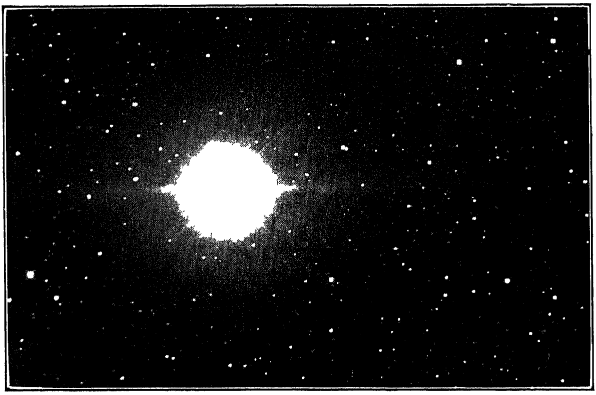


Fig 13 Star field in Auriga
Showing stars to the seventeenth magnitude

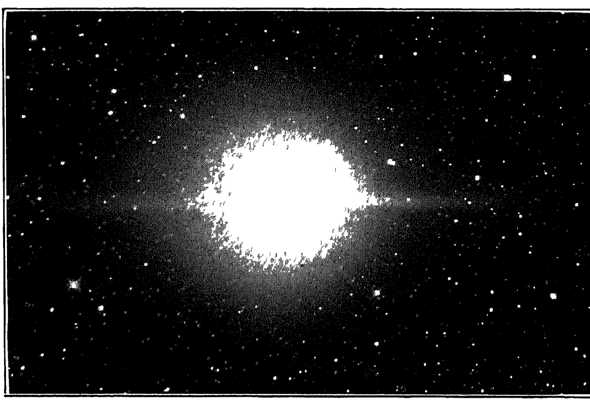


Fig 14 Star field in Auriga
Showing stars to the eighteenth magnitude

The method of trigonometric parallaxes, which measures a star's displacement as seen from opposite ends of the earth's orbit, is limited in its application to the nearer stars This is because the angular displacement of stars more than a few hundred light-years distant is too minute for measurement, even with all the exquisite refinement of the latest instrumental and photographic methods In penetrating greater depths of space we must have recourse to still more powerful means, which fortunately have recently been discovered and applied.

Consider the bright star Sirius, and call its distance unity If it were moved to distance 2, its apparent brightness, which decreases as the square of the distance, would be one-fourth At distance 4, it would be one-sixteenth, at distance 8, one sixty-fourth, etc If, then, we knew the absolute or intrinsic brightness of a star, *i e*, the brightness it would have at unit distance, its easily measured apparent brightness would give us at once a measure of its actual distance

But how are we to determine its absolute brightness? This apparently insoluble problem has recently yielded to a vigorous attack, which has greatly extended our means of sounding space By the new method of Doctor Walter S Adams it has become

graphic effect, and has no relationship to the true diameter of the star The circle in Fig 12 results from reflection of the light from the back of the plate The straight lines, like rays, that project from the largest images are diffraction effects caused by the metal bars that support the small mirror at the upper end of the telescope tube

possible to determine the distance of a star of known apparent brightness from simple estimates of the relative intensities of certain lines in its spectrum

SPECTROSCOPIC MEASURES OF STELLAR DISTANCE

Strontium chloride, when placed in the blue flame of a Bunsen gas-burner, colors it a brilliant crimson—the effect of a strong line in the red part of its spectrum This line, with several others of smaller intensity, can be seen with an ordinary one-prism spectroscope These radiations are characteristic of the strontium atom, which recent investigations have shown to be composed of thirty-eight electrons, presumably rotating about a positively charged central nucleus.

We can change this spectrum very decidedly, however, by placing some strontium chloride in an electric spark, which ionizes the vapor This means that the intense electric discharge tears away one of the electrons circling about the nucleus of the atom, leaving a positively charged system minus one negative electron Intense heat or a reduction of pressure is competent to produce this disruption of the strontium atom and to give rise to certain lines in the spectrum that are weak or wholly absent at low temperatures or high densities of the radiating gas Two of these "enhanced" lines, in the blue part of the spectrum, known to spectroscopists as $\lambda 4077$ and $\lambda 4215$, when contrasted with a line of calcium ($\lambda 4454$), which is strongest at low temperatures or high densities, are able to give us an

extraordinary amount of information regarding the absolute brightness, and hence the distance of the stars These lines are mentioned merely as typical examples of the two great groups of enhanced and low-temperature lines, which are exhibited by many different elements in varying degrees of intensity in the various stages of stellar life.

Stellar spectra are photographed on Mount Wilson with the aid of the 60-inch and 100-inch reflecting telescopes A spectroscope arranged for photography is mounted at the focus of the telescope, and the image of any desired star is brought to the slit by moving the telescope with electric motors When exactly on the slit, through which its light passes for analysis by one, two, or three prisms, the star is held in position by the driving-clock of the telescope The observer constantly watches the star on the slit so as to correct any wandering of the image by means of a motor, which slightly accelerates or retards the driving rate of the clock The exposure varies from a few minutes for the brighter stars to several hours for very faint ones In this way the spectra of thousands of stars, down to the limit of visibility of Herschel's telescope, are photographed one by one for study

While examining these plates Adams and his associates on Mount Wilson have given special attention to certain lines because of their changes of intensity in the hotter and cooler regions of the sun (or at high and low levels in the sun's atmosphere), and their corresponding behavior in laboratory ex-

iments The distance of some of the stars in ich such lines were observed had been determined the method of trigonometric parallaxes, and con-

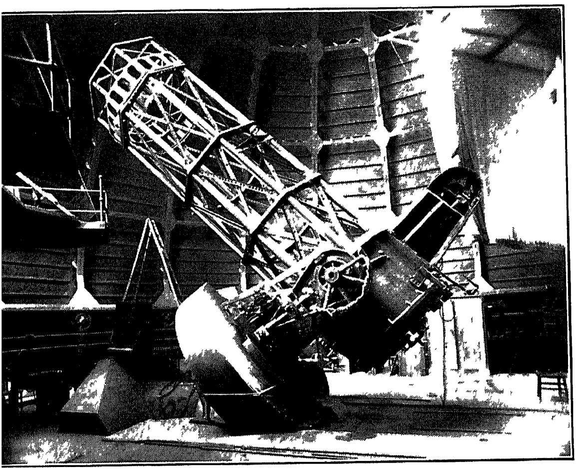


Fig 15 The 60-inch reflecting telescope of the Mount Wilson Observatory

this arrangement of the instrument the light from the star under observation, after falling on the 60-inch concave mirror at the lower end of the tube, is reflected back to the smaller convex mirror near the upper end This returns the narrowing cone of light to a plane mirror at the intersection of the declination and polar axes, which reflects it upward to the focal point at the side of the tube Here it passes through the narrow slit of the spectrograph, then through a collimating lens and two prisms and finally through the camera lens to the photographic plate, where an image of the star's spectrum is recorded The task of the observer is to watch the slit through a small auxiliary telescope throughout the exposure, and to move the large telescope slightly from time to time by an electric motor, in case the driving-clock fails to maintain the star's image exactly on the slit

quently their absolute or intrinsic brightness was iown It soon appeared that in stars of great intinsic brightness some lines are exceptionally strong

while others are weak In certain of these, for example, the "enhanced" or spark lines of strontium are very strong, while the calcium line λ4454 is weak. In intrinsically faint stars the reverse is

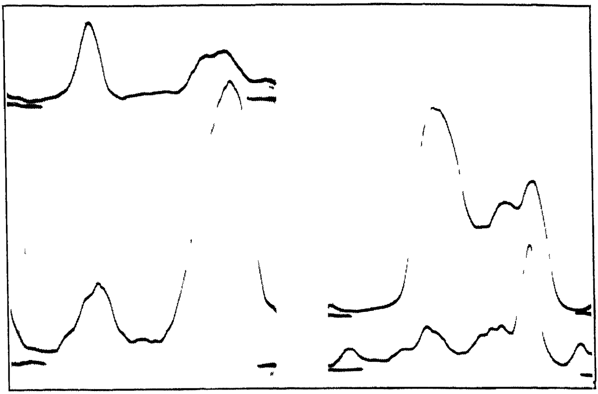


Fig 16 Curves which show the relative intensities of pairs of lines in dwarf and giant stars (Adams)

These curves were obtained with a self-registering microphotometer, in which the light transmitted by the photographed special lines draws a chart upon a sensitive plate

The left-hand diagram shows the relative intensities of λ4071 (left) and λ4077 (right) in the dwarf star η Cassiopeiæ (above) and the giant star Polaris (below) The line λ4077 is very much stronger in the lower star Similarly the right-hand diagram shows the relative intensities of λ4454 (left) and λ4461 (right) in the dwarf star 61 Cygni (above) and Aldebaran (below) The line λ4454 is in this case much stronger in the dwarf star

true—the calcium line is stronger than the strontium lines. It thus became possible, in fact, to determine a definite numerical relationship between the intrinsic brightness of a star and the relative strength of these lines Turning, then, to a star of

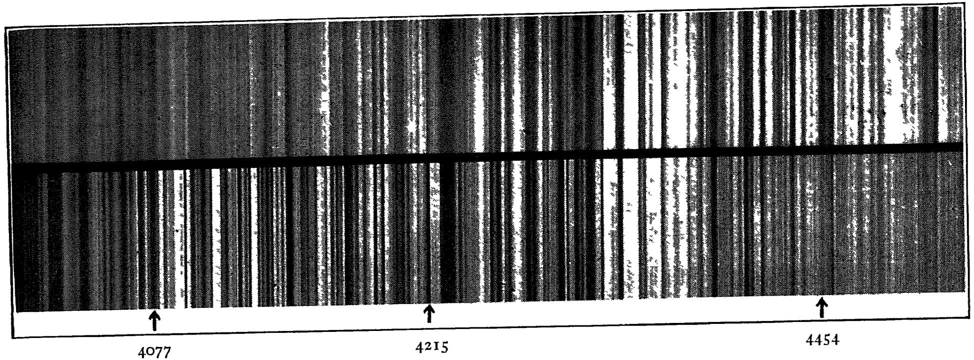


Fig 17 Spectrum of 61 Cygni, a dwarf star, compared with that of Aldebaran, a giant star of nearly the same spectral type (Adams)

The principal lines used in determinations of absolute magnitude are indicated Many other differences may be seen from a simple inspection

unknown distance, a simple estimate of the relative intensity of the calcium line and one of the strontium lines then gives a measure of its absolute magnitude. Knowing its apparent brightness, its distance at once follows.

The ease and quickness of application of this method render it very advantageous in studies of the structure of the universe. Unlike the trigonometric method, its use is not restricted to the nearer stars. It may thus carry our sounding-line deep into space, where distances are reckoned in thousands of light-years. Prior to 1900 only 60 precise measures of stellar distance had been made by the laborious methods, for the most part visual, applied up to that time. The work of Schlesinger with the 40-inch Yerkes telescope initiated an American school of parallax measurers, whose efficient use of photographic methods added new and more precise determinations at such a rapid rate that the total number of trigonometric parallaxes is now about 1,400. In 1915 Adams and his associates began systematic application with the 60-inch telescope of his spectroscopic method, which was subsequently extended to the 100-inch telescope and has already yielded over 2,000 determinations of stellar distance. In a future article some of the important conclusions based on these new results will be described. They not only prove decisively the existence of dwarf and giant stars, but also throw a flood of light on the structure and evolution of the stellar universe.

STAR CLUSTERS

Another method of measuring distances has been used by Doctor Harlow Shapley, now Director of the Harvard College Observatory, in his extensive

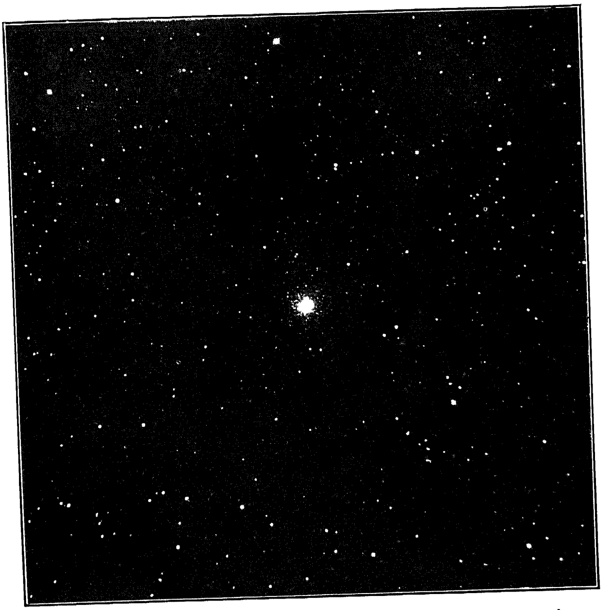


Fig 18 Globular star cluster N G C 7006 (Shapley)
Shapley finds its distance to be about 220,000 light-years

investigation at Mount Wilson of globular star clusters The constellation of Orion is one of the most beautiful of celestial objects, both to the naked eye and under closer scrutiny in the telescope The

brilliant stars that outline the figure of the giant hunter and mark his girdle are scattered over a vast expanse of sky, but all of them except Betelgeuse constitute a definite physical group, doubtless of common origin and still moving together through space This is an excellent example of an open star cluster, repeated in Ursa Major and again in the more condensed groups of the Hyades and the Pleiades, both of which are also true physical systems.

This clustering tendency is widely illustrated among the stars The simplest case of stellar grouping is that of the binaries, in which we observe two stars, frequently larger than the sun, revolving about their common centre of gravity. Thousands of such double stars have been found, in some cases accompanied by a third member. Groups of this kind differ materially from open clusters of the Orion type, where the widely separated members do not revolve about a common centre, but move in nearly parallel lines through space But the most striking of all stellar systems are the great globular clusters which have been used by Shapley for a study of the dimensions of the stellar universe. Only ninety-five of these highly condensed clusters are known, and the problem of determining their distances and dimensions is of fundamental importance

Several years ago, in an examination at the Harvard Observatory of photographs of the small Magellanic Cloud, the late Miss Leavitt gave special

attention to certain stars of the Cepheid class, which fluctuate in brightness in regular periods ranging from 1.25 to 127 days. By comparing the average

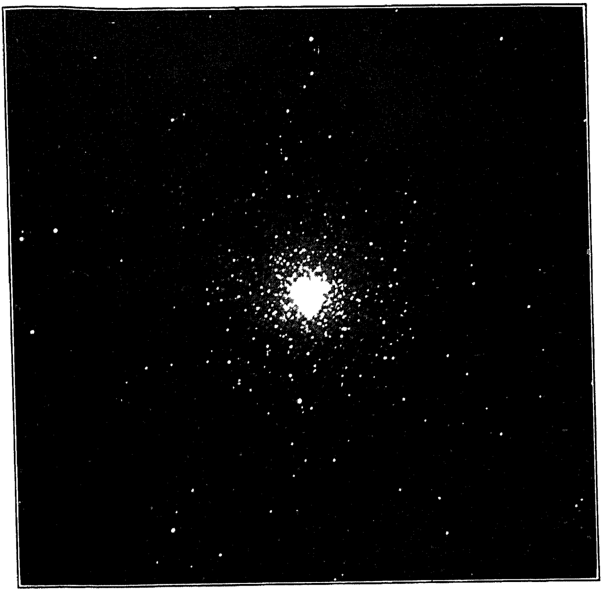


Fig. 19. Globular star cluster Messier 79 (Shapley)
Shapley finds its distance to be about 85,000 light-years

apparent brightness of each star with its period of variation, she detected a definite relationship between the two. Thus, if in any star of this class only the period were known, its average brightness could be accurately predicted. As all of the stars

in the Magellanic Cloud are at essentially the same distance from the earth, the differences in their apparent brightness correspond to differences in absolute or intrinsic brightness Thus this simple method, if it holds strictly for all variables of the Cepheid class, should provide a means of determining the absolute brightness of such a star, however remote, from the length of its period As we have already seen in Adams's spectroscopic method, as soon as we know the absolute brightness of a star a knowledge of its apparent brightness gives us its distance

DISTANCE OF GLOBULAR CLUSTERS

By this means, and also by other methods, Shapley determined the distances of all globular clusters photographed with the 60-inch and 100-inch telescopes. With long exposures these instruments show them to be composed of many thousands of stars, grouped in globular form The great cluster in Hercules, for example, contains fully 35,000 stars as bright as the sun, and some of these are more than a thousand times brighter Among them are many Cepheid variables, and by observing their periods and their apparent brightness, their absolute brightness and hence their distance has been found This reaches the immense figure of 36,000 light-years

If this measure is correct, and there is much independent evidence to support it, we take a tremendous leap into space and time when we reach

out to this cluster We have seen that light travelling at the rate of 186,000 miles per second requires 1 2 seconds to reach us from the moon, 8 minutes to come from the sun, and 4⅓ years to cross the space between us and the nearest star Our views of such objects are thus contemporaneous, or nearly so we see them as they are now or as they were within a few years But the Hercules cluster is in another class The light that left it 36,000 years ago, travelling at the rate of nearly six million million miles per year, has only just reached us Thus, we cannot say how the cluster appears to-day, or whether it has existed at all since the dawn of our civilization There is every reason to believe, however, that if we could see the present cluster—as astronomers will see it 36,000 years hence—it would appear essentially as it does in our photographs of its remote past For 36,000 years is as a day in the cycles of the universe, where millions of years bring little change.

Look at the cluster as shown in Fig 20. All of the stars that appear in this picture, as already remarked, are brighter than the sun The immense size of the cluster is indicated by the short horizontal line drawn on the centre of the image, which represents the distance from the earth to α Centauri—4⅓ light-years The diameter of the large circle is 10,000,000 times the distance from the earth to the sun, or 160 light-years The total diameter of the cluster, which extends far beyond this circle, is more than 350 light-years

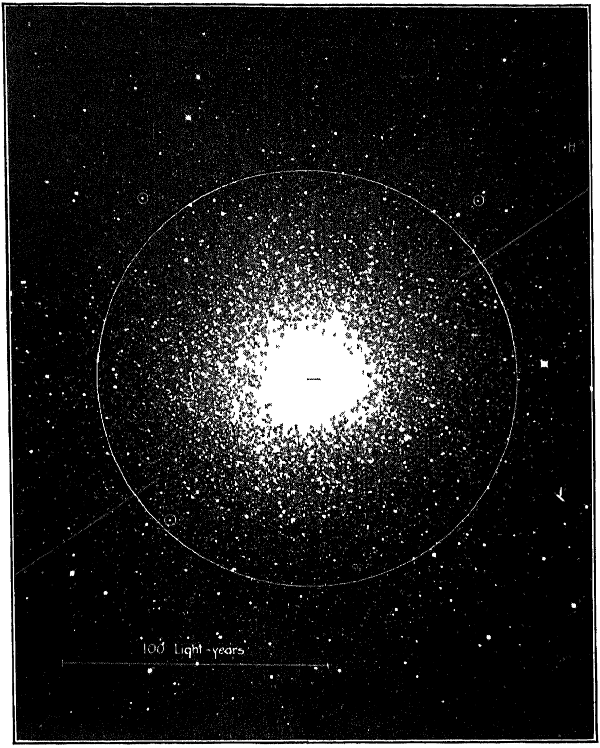


Fig 20 Great globular star cluster in Hercules (Ritchey)

Shapley finds the distance of this cluster to be 36,000 light-years On this basis over 35,000 of its stars are as bright as the sun, while the three stars in the small circles are one hundred times as bright The length of the short line at the centre is 4⅓ light-years, and the diameter of the large circle is ten million times the distance from the earth to the sun, or 160 light-years

This enormous star system, according to Shapley, is one of the nearest of the globular clusters One cluster lies at a distance greater than 200,000 light-

years, and beyond this may be others still more remote. They appear to be isolated systems, not closely associated with the stars, but nevertheless so distributed that they belong to the great stellar universe represented by the Galaxy. The distance of the Hercules cluster is about the same as that of the star clouds of the Milky Way recently measured by Seares. These measures relate to stars down to the fifteenth magnitude, but many of the fainter stars must be much more distant, perhaps as remote as the farthest globular cluster.

SIZE OF THE GALACTIC SYSTEM

Thus we may think of the galactic system as a flattened disk or watch-shaped aggregation of stars, having a diameter of perhaps 300,000 light-years, with the sun at a very considerable distance from the centre. The thickness of the disk is about one-eighth of the diameter, or 37,500 light-years. These great dimensions have been denied by Curtis, who argues in favor of a galactic system about one-tenth as large. But more and more evidence is accumulating in favor of the larger conception of Shapley, which has already found wide acceptance among astronomers.

The question at issue, it should be emphasized, is the size of the galactic system of stars to which the sun belongs. This includes all the stars within reach of observation, together with the planetary nebulæ and the irregular galactic nebulæ, both bright and dark. It does not necessarily include,

however, the very remarkable spiral nebulæ, about a million of which can be photographed with the largest telescopes The question has not yet been settled whether these are no farther from us than the more distant stars or whether they should be regarded as "island universes," isolated in the depths of space and comparable in size with the galactic system Curtis, who holds the latter view, estimates their distance to range from 500,000 to 10,000,000 light-years, while Shapley, van Maanen, and others believe them to be much nearer Interesting arguments have been advanced on both sides, but these are too numerous to be presented here

The vast scale of the universe easily explains phenomena that were once obscure Even the moderate distance of 350 light-years causes a star like Antares, more than 400 times the sun in diameter, to shrink to a tiny point too small to be magnified by any telescope into a true disk Thanks to Michelson's interferometer, used with the 100-inch telescope, the diameter of Antares and that of a few other stars have been measured by indirect means * In this and other ways great modern instruments have rapidly advanced our knowledge of the structure of the universe and enabled us to sound its depths and to trace the evolution of the stars

* See "The New Heavens," Charles Scribner's Sons, 1922

BARNARD'S DARK NEBULÆ

THE most impressive of celestial objects is the luminous girdle of the Galaxy. Seen through transparent air on a moonless night, its intricate cloud masses glow with a steady light behind a curtain of twinkling stars. Since the time of Herschel the Galaxy has been recognized as the core of the stellar universe, that vast assemblage of some two thousand million stars, shaped like a flattened disk, near whose centre the solar system is moving in its journey through space. When observing the Milky Way we are looking out through the lucid stars in the central area toward the periphery of this immense system, whose shining coils result from the mingled glow of countless remote stars.

In the previous chapter it has been shown that our conception of the scale of the stellar universe has grown with time. Seares has recently found that several of the galactic clouds range in distance from 20,000 to 50,000 light-years, as measured by the blue stars of magnitude 14 to 15.5, which marked the limit of Herschel's telescope. These results are in harmony with Shapley's estimate of a total diameter of at least 300,000 light-years for the Galaxy. We may thus realize to what extraordinary depths our great telescopes penetrate when, aided by photog-

raphy, they bring to view the excessively faint stars that lie near its outer limits

HERSCHEL'S "HOLE IN THE HEAVENS"

Into one of the most luminous of the galactic clouds, not far from the common boundary of the

Fig 21 The great obscuring nebula of Rho Ophiuchi
Photograph by Barnard with the 10-inch Bruce telescope

constellations of Ophiuchus and Scorpio, Sir William Herschel had been led in his systematic sweeps of the heavens. His process of "star-gauging," used for the purpose of determining the structure of the universe, had carried him step by step from the comparatively vacant regions near its poles to the dens-

est part of the Galaxy, where the stars are clustered in swarms Here he suddenly encountered an obscure area, as though the whole thickness of the stellar system, along its greatest extension, had been tunnelled through into starless space beyond No wonder that he looked long and earnestly, during what his sister (always his assistant) chronicled as "an awful silence," before he exclaimed: "Surely this is a hole in the heavens!"

Thanks to modern photography, it is possible for the reader to examine this region of the sky even more advantageously than Herschel could with his powerful telescope. Fig 21 shows (just above the centre of the cut) the bright nebula surrounding the star Rho Ophiuchi and a great dark area, with long dark lanes extending to the east. The star cluster Messier 4 is seen near the lower edge of the cut. On its left is the bright red star Antares (Alpha Scorpii), while the star Sigma Scorpii lies in the bright nebula above and to the right of the cluster Herschel, using a higher magnifying power, could see only a small part of this field at once While the identification of the exact region that caused his exclamation is uncertain, it was probably a part of the dark starless area to the left of the centre of the photograph His first idea was that the stars which formerly occupied these voids might perhaps have been withdrawn in the course of ages to form such clusters as that near Antares Deeply impressed by this vast obscurity, he examined it again and again, but could never arrive at a satisfactory explanation

of its origin. Indeed, a century was to pass before its true meaning could be fathomed

Meanwhile, from its simple beginnings in the hands of Daguerre, photography had advanced to a perfection which rendered it the chief aid of the astronomer First applied to the registration of stellar images by Bond at the Harvard Observatory in 1850, its value soon became generally recognized, and it has served in all parts of the world for mapping the heavens Few objects are now observed visually, and tens of millions of stars and nebulæ beyond the reach of the eye have been discovered by photographic means

Any one who owns a camera can soon ascertain for himself its power of recording stars Open the iris diaphragm to its extreme limit, so as to uncover the full aperture of the lens Point the camera toward any group of bright stars, and clamp it firmly to a rigid support, fixed where street or house lights do not shine into the lens. After an exposure of say half an hour, give the plate or film full development, and the trails of the stars will appear In general they will be arcs of circles, deeply concave and centered on the pole, when the camera is pointed due north, (Fig 22), straight when it is directed toward the celestial equator If the exposure is continued for six hours, the arcs drawn by circumpolar stars will become quadrants They are due, of course, to the rotation of the earth on its axis, which causes the stars to complete an apparent rotation about the pole, from east to west, in twenty-four hours

To overcome this motion, and thus hold the star images fixed on the plate throughout the exposure, it is necessary to mount the camera equatorially, in such a way that it can be pointed toward any part

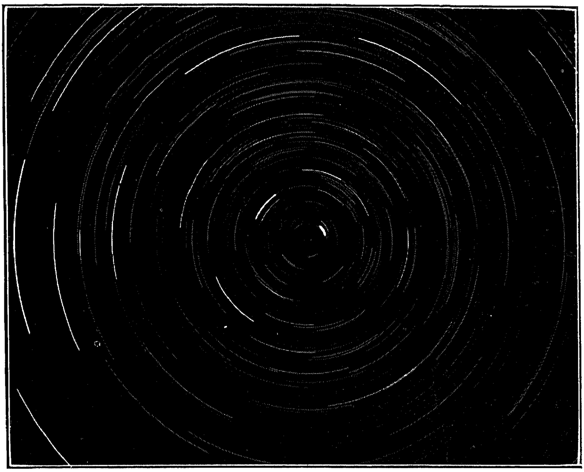


Fig 22 Star trails at the North Pole (Ellerman)
Photographed with a stationary camera

of the heavens and then moved by a driving clock about an axis parallel to the axis of the earth, at the exact rate (one revolution in twenty-four hours) necessary to keep perfect pace with the stars Fig 23 shows the Bruce telescope of the Yerkes Observatory, a steel camera with an excellent Brashear lens of 10 inches clear aperture and 50 inches focal length, mounted equatorially in the admirable man-

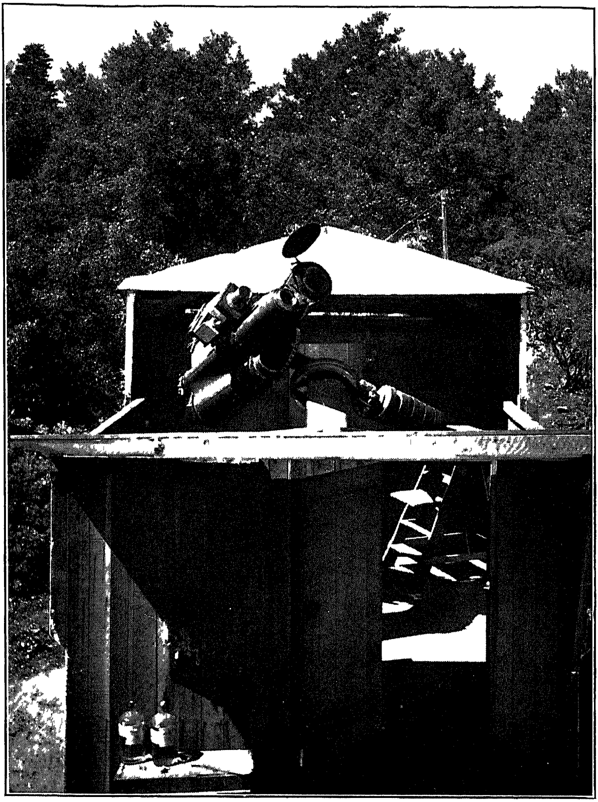


Fig 23 The Bruce telescope as temporarily erected at Mount Wilson for the photography of the Milky Way

ner characteristic of the firm of Warner & Swasey. The same mounting also carries a 6-inch camera and two other cameras of smaller size For it is a

noteworthy fact that even the small lenses commonly used for landscape photography may be of great service, when properly mounted, for astronomical purposes.

BARNARD'S PHOTOGRAPHS OF THE GALAXY

The photographs of various regions of the Milky Way reproduced in Figs. 21, 26, 28, 29, and 31 were taken by the late Professor Barnard with the Bruce telescope on Mount Wilson in 1905. Between January and September of that year he made 161 negatives (12 inches square) with the 10-inch lens, 175 (8 x 10 inches) with the 6-inch lens, and many others with the smaller lenses. Forty-eight of these plates, beautifully reproduced under Professor Barnard's supervision, are to appear soon in a photographic atlas of the Milky Way, to be published by the Carnegie Institution of Washington. The text for this volume, which was nearly completed by Professor Barnard, is being put in form for publication by Professor Frost, Director of the Yerkes Observatory. In addition to other photographs of the Milky Way taken at the Yerkes Observatory, it will contain a complete catalogue of some two hundred dark objects, of the type described by Herschel, discovered by Professor Barnard on his photographs, together with a discussion of their nature.

The death on February 6, 1923, of Edward Emerson Barnard, one of the greatest of American astronomers, was an irreparable loss to science. Never since the days of Herschel has there been such an

eager observer or such a living storehouse of celestial knowledge He constantly watched the heavens, and never lost an opportunity, however slight, to study their changing phenomena. Although his observations of every class of celestial objects, stars, nebulæ, comets, planets, satellites, meteors, and many others, were numbered by tens of thousands, he could always recall the day and often the hour of any one of them, as well as the exact details recorded. His tireless enthusiasm and his persistence in the heavy task of observing throughout the bitter nights of winter hastened his death, which is so deeply felt by his many friends.

Barnard was a magnificent example of that high regard for the exact and unqualified truth which the genuine man of science must embody In him the passion for honest and undistorted fact dominated every personal preference and held him far above the plane of those whose chief concern is to demonstrate some favorite hypothesis, at whatever disregard of opposing evidence. No finer illustration of the ideals of science could be found than in this simple, sincere, and lovable astronomer, whose one and only object was to extend the boundaries of knowledge. He greatly succeeded, and his name is recorded in the rolls of the foremost explorers of the heavens.

A DARK NEBULA IN SAGITTARIUS

Many of the dark markings of the sky were discovered by Barnard during his photographic work

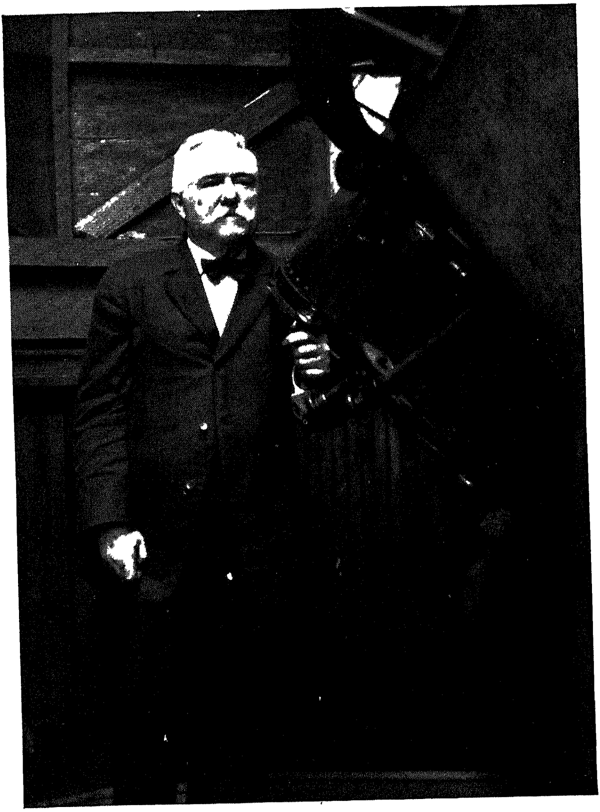


Fig 24 Edward Emerson Barnard at the Bruce telescope

at the Lick Observatory, where I first met him in 1890, when he was a member of the original staff But his first observations of such phenomena date

from an earlier period, when he made his name as a discoverer of comets while a photographer's assistant at Nashville. In a recent paper in the *Astrophysical Journal*, "On the Dark Markings of the Sky," he speaks especially of a remarkable dark spot, black as an ink drop, in Sagittarius (No. 86), which appeared in his 5-inch comet-seeker as one of the most impressive objects in the Milky Way. In 1895 he examined it with the 36-inch Lick refractor, where, with a magnifying power of 350, it nearly filled the field of view. It was fairly well defined on the west, but more diffuse on the east, and there seemed to be considerable nebulosity connected with it, a significant fact subsequently confirmed photographically by Curtis with the 36-inch Crossley reflector. A later photograph, taken in 1921 by Duncan with the 100-inch Hooker telescope at Mount Wilson, is reproduced in Fig. 25. It shows a few small stars in front of the intensely black nebular cloud, but the rich background of still fainter stars, more remote than the nebula, is lacking. A cluster of relatively bright stars appears close by on the left.

In considering the appearance of the dark objects in the photographs, the reader should bear in mind the nature of the instruments with which they were taken. Figs. 21, 26, 28, and 29 show very large regions of the sky on a small scale, taken with a camera of 50 inches focal length, provided with a large portrait lens of 10 inches aperture (the Bruce telescope). Figs. 25, 27, 30, and 32, on the contrary, show small areas of the sky on a large scale, taken

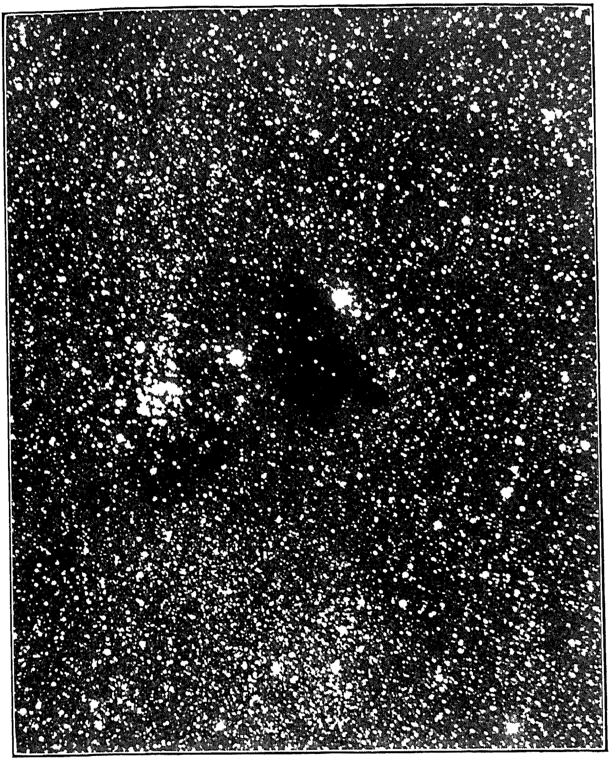


Fig 25 Barnard's dark nebula No 86

Photographed by Duncan with the 100-inch Hooker telescope of the Mount Wilson Observatory

with a camera of 43 *feet* focal length, with a mirror (instead of a lens) of 100 inches aperture (the Hooker telescope) While the 100-inch telescope serves much better than the Bruce for some pur-

poses, the latter has the advantage of bringing before us a large region of the sky in a single photograph, and of accentuating the blackness and definiteness of objects that might not be detected with a

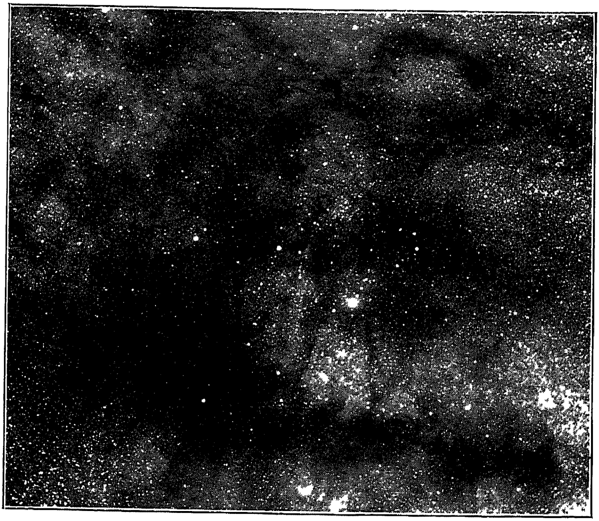


Fig 26 Dark markings in the Milky Way about the bright star Theta Ophiuchi

Photographed by Barnard with the Bruce telescope

large telescope because of their diffuse character in long-focus instruments When once recognized on the portrait lens plates, however, their detailed study with a large telescope becomes essential Even under the searching scrutiny of the 100-inch reflector, the sharpness and blackness of some of the dark

nebulæ are so great that their images remain very distinct, as in the case of Barnard's No 86 (Fig 25) But in other instances such strong contrast is lacking, or the object may be so large as to cover the entire field of the 100-inch telescope.

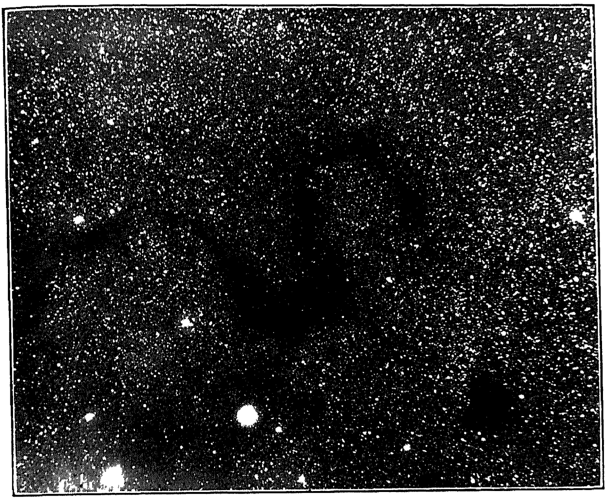


Fig 27 Barnard's dark nebula No 72, in Ophiuchus
Photographed by Duncan with the Hooker telescope

In the region about the bright star Theta Ophiuchi many dark markings, both large and small, are found (Fig 26) Some of these are very peculiar in form, and do not resemble any of the bright nebulæ Nevertheless the evidence indicates that most of them are dark, obscuring masses, which cut off the

light of the distant stars and leave visible only those that lie between the dark masses and the earth. The S-shaped area in the middle of Fig. 26 is Barnard's No 72, shown on a large scale in Duncan's

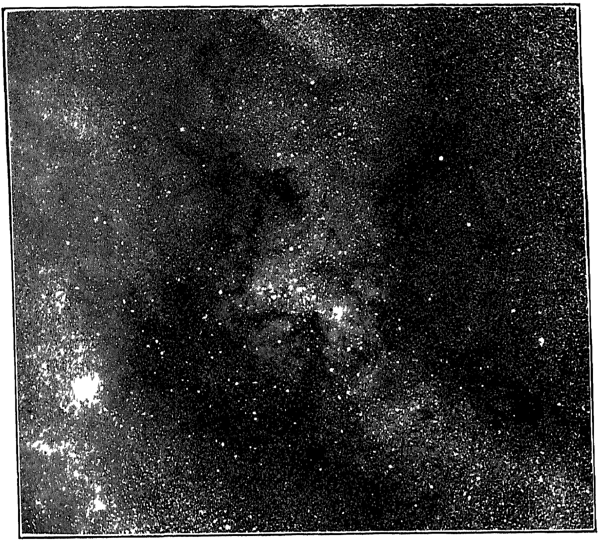


Fig 28 Dark markings in a great nebula in Cepheus. Photographed by Barnard with the Bruce telescope

photograph with the 100-inch telescope (Fig. 27). Another fine region of the Milky Way photographed by Barnard is that in Cepheus, where many dark objects also appear (Fig 28) Some of these are superposed on the great bright nebula that occupies the central area of the picture

Thus far we have been considering the darker areas, some of which appear inky black when observed visually with a telescope. It is evident that if these are actually obscuring masses, lying between us and the more distant stars, they should be most conspicuous where the luminous background is brightest and most continuous, as in the crowded regions of the Milky Way. Barnard's photographs show this to be the case. With a very large telescope many stars too faint to be recorded on the Bruce photographs are seen, but these do not produce the luminous background. It results, according to Barnard, from myriads of small stars not visible even with the 40-inch Yerkes telescope.

Such stars are shown by Seares's long-exposure photographs with the Mount Wilson 60-inch reflector to be very numerous in the great clouds of the Milky Way, but they are comparatively few in number in the sky away from this region. Nevertheless, Barnard has found many dark objects in such areas of few stars. He gives as a notable instance No. 15 in his catalogue, elliptical in form, its longer axis equal to half the moon's diameter. "The background on which the stars shine is uniform over the entire plate. The object is in a region somewhat larger than itself, where there are relatively few stars, and is black by contrast with the sky alone. It clearly shows the presence of a feeble uniform luminosity in space which, from the appearance of similar objects in widely different parts of the sky, leads to the belief that this feeble illumination of distant

Fig 29 Great star cloud in Sagittarius

Photographed by Barnard with the Bruce telescope The dark nebula No 92 appears near the middle of the cut

space is universal If this object were seen against the star clouds of the Milky Way it would appear strikingly black"

FAINTLY LUMINOUS NEBULÆ

Without attempting at present to discuss this feebly luminous background of the entire heavens, we may turn to the examination of obscuring neb-

ulæ which, though they blot out the stars beyond them, seem to be slightly luminous themselves Barnard's No 92, the apparently black elliptical object in the centre of Fig 29, is of this class

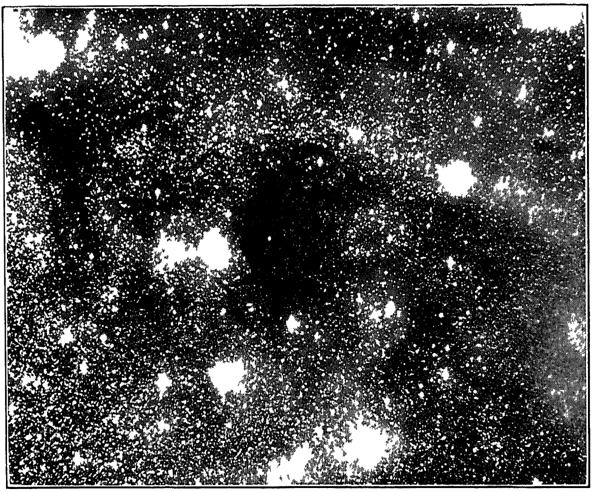


Fig 30 Barnard's dark nebula No 92
Photographed by Duncan with the Hooker telescope

Lying against a bright star cloud in Sagittarius, it resembles on the Bruce photograph the inky black object No 86, which has been described on page 46 and illustrated in Fig 25 But Barnard found, in a careful visual examination of No 92 with the 40-inch Yerkes telescope, that it is in reality faintly luminous Thus its appearance of blackness in the

Bruce photographs is chiefly due to an effect of contrast against the brilliant background of the Milky Way Duncan's large-scale photograph of this object with the Hooker telescope, reproduced in Fig

Fig 31 Partially dark nebulæ and dark lanes in Taurus
Photographed by Barnard with the Bruce telescope (6-inch lens)

30, clearly shows the luminosity—although it is scarcely visible in the illustration

Any doubt one might retain as to the luminosity of certain obscuring regions may be removed by an examination of Fig 31, a reproduction of Barnard's Bruce telescope photograph of a rich star cloud in Taurus Above and to the right of the centre of the cut is a large region which appears almost totally

dark except for a small bright nebula and a few stars superposed upon it. Leading from this region to the left, however, is a long lane which, though nearly devoid of stars, in some parts is of about the same intensity as the general background of neighboring areas in which stars are numerous A similar long lane near the bottom of the cut is still more striking in this respect From these and many similar instances, it cannot be doubted that some of these nebulæ, though sufficiently obscure to obliterate most, if not all, of the stars beyond them, are partly luminous themselves

In my book "The New Heavens" mention has been made of the luminous nebulæ in Orion. One of them, faint but of colossal size, completely surrounds the entire constellation, while the bright nebula in the sword-handle, though small by comparison, is one of the most striking of telescopic objects Thanks to the large reflectors, we find that the most remarkable of the dark nebulæ is also in Orion. Discovered long ago, the peculiar object shown in Duncan's photograph is too small to be effectively photographed with a short-focus telescope It is evidently part of an immense obscuring mass, which blots out most of the stars on the left of the picture and projects, with its luminous border, in front of the star-filled area on the right This photograph also shows a bright nebula on the left, above the centre of the cut (Frontispiece)

Space is lacking to describe the hundreds of careful tests, both visual and photographic, which finally

convinced Barnard of the existence of dark nebulæ The value of his testimony is enhanced by his scepticism in 1894, when Mr A C Ranyard reproduced one of Barnard's Lick Observatory photographs in his journal, *Knowledge* Commenting on the dark lanes in this photograph, Ranyard remarked "The dark vacant areas or channels running north and south of the bright star [Theta Ophiuchi] at the centre seem to me to be undoubtedly dark structures, or obscuring masses in space, which cut out the light from the nebulous or stellar region behind them." Barnard says that he "did not at first believe in the dark, obscuring masses," and I recall that I shared his doubts At present there seems to be no room for question

COSMIC DUST

We are thus called upon to recognize the existence of a new class of astronomical objects, which cover extensive and widely distributed areas of the heavens It usually happens that the discovery of celestial phenomena precedes their interpretation by many years, but in this case, thanks to Doctor Henry Russell, a satisfactory explanation is already at hand To understand it we must recall the existence of a force which, while feeble on the earth, is very powerful in the hotter stars

The pressure exerted by a beam of light, even from the most brilliant terrestrial sources, is so slight that great ingenuity was required to detect and measure it. The well-known American physicists

Nichols and Hull devised and built in 1901 a radiometer for this purpose, which left no doubt as to its reality or magnitude Subsequent theoretical investigations by Schwarzschild showed that for particles of dust a few millionths of an inch in diameter, and of the density of water, the repulsive force of the sun's radiation is about ten times as great as its gravitational attraction For dwarf stars, later in point of development than the sun, the repulsion is less, but the giant white stars of Class B repel such minute dust particles fully ten times as powerfully as the sun. Larger dust particles, which are less vigorously repelled, can exist near stars, but the finer ones will be driven away into space, where they may form the obscuring clouds revealed by Barnard's photographs As the finest dust is always repelled by the stars, whatever their distance, it must continue to move toward the most remote depths of space Sometimes it may attain regions where the repulsion from stars lying in opposite directions is nearly balanced, but it can never find a condition of perfect equilibrium How, then, are the definite dark clouds to be accounted for?

Russell points out that as their outlines are often sharp, some force must hold the clouds together. This may be the gravitational attraction of the constituent dust particles acting on each other There is reason to believe that the aggregate mass of some of the obscuring clouds is enormous—as great as that of hundreds of stars Calculation shows that the mutual attraction of their particles would hold them

together, unless these particles are moving at higher velocities than indications suggest

The effect of such a cloud in cutting off the light of more distant stars depends upon the size, density, and number of the particles that compose it Particles of the most effective size (with a circumference 1 12 times the wave-length of the incident light) produce a marked obscuring effect, so that a comparatively small amount of matter, divided into dust of this fineness, will easily account for some of the observed phenomena Moreover, particles of this size are precisely those most vigorously repelled from the stars.

The appearance in space of these clouds of cosmic dust will depend upon their environment If remote from bright stars, and observed against a luminous background, they will be recognized as obscuring masses, capable of obstructing the light from the more distant sources If close to bright stars they may reflect to us some of their light, as Slipher has shown to be the case in the nebulæ surrounding the Pleiades Or, in harmony with the theoretical investigations of Russell and the recent observations of Hubble at Mount Wilson, the radiation from the stars may excite a secondary emission of light by gaseous molecules associated with the dust particles.

THE NATURE OF NEBULÆ

An account of Hubble's remarkable results must be reserved for future publication, but they may be briefly mentioned here The character of the spec-

trum of a nebula, whether continuous, with dark lines, or composed of bright lines, depends upon the temperature of conspicuous stars, obviously involved in the nebula The extent and brightness of the nebulæ are also found to be proportional to the

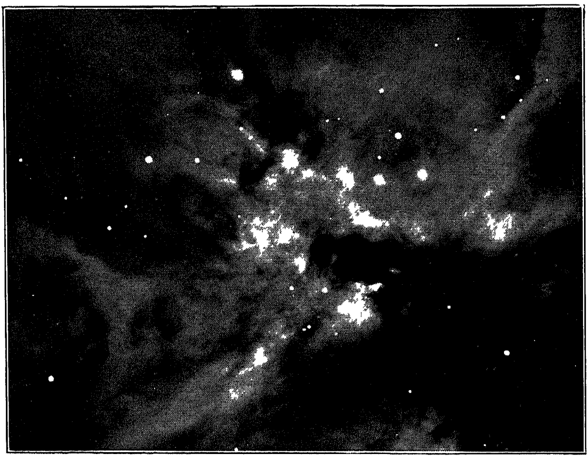


Fig 32 Central part of the Great Nebula in Orion
Photographed by Pease with the Hooker telescope

brightness of the stars involved The conclusion is that these stars are the source of nebular luminosity, which in some cases may be simply reflected starlight while in others it is starlight absorbed and re-emitted by the gaseous constituents of the nebula.

With all of these results in view, Russell draws for us an entirely new picture of the Great Nebula in Orion (Fig 32) We have long been accustomed to

think of this brilliant object as a mass of glowing gas, but the cause of its luminosity has never been understood Russell sees it as an enormous plenum in which wisps and clouds of dust, carrying molecules of gas with them, are in constant motion Those that pass into the neighborhood of the four bright stars of the Trapezium are excited into luminosity by their brilliant radiation, giving us the characteristic nebular spectrum, which fades away toward the faint outlying regions On this hypothesis the dark masses shown in Fig 32 are obscuring clouds of dust, dense enough to be quite opaque to light coming from behind them. If this view is correct, the Orion nebula, as we see it, is chiefly a superficial fluorescence of the gaseous elements in a small region of an inconceivably great cloud of cosmic dust, driven to and fro by never-ceasing currents These produce constant changes of form, which at the distance of the sun (8 light-minutes) would be perceptible after a short interval of time But at the far greater distance of 600 light-years, the most careful comparative measures of large-scale photographs, taken at intervals of many years, will be required to reveal them.

What a picture of the stellar universe is thus presented to the imagination! Myriads of stars, many of them far larger than the sun, organized in a system so vast that light cannot traverse it in less than three hundred thousand years Each star a powerful centre of attractive and repulsive forces, drawing into it, at meteoric velocities, all masses enter-

ing its neighborhood at moderate speeds, driving from it electrons and other minute particles, which its repulsion pursues into the most distant regions of the universe. Each particle, moving with millions of its kind through the highways and crossroads of space, or drawn with its companions into masses by mutual attraction, aiding to form great cosmic clouds, dark and obscuring when far from brilliant stars, luminous with the spectral hues of the lightest gases when exposed to intense stellar excitation. And this is but half the picture, for every particle of gas or dust is built of countless molecules, and these in turn of atoms, each comprising an ultramicroscopic world, in which the whirling electrons, like the planets of the solar system, move in their orbits about a positive nucleus—their central sun.

SUN-SPOTS AS MAGNETS

SUN-SPOTS have been known since the third century of our era, though the western world held its belief in an immaculate sun until the invention of the telescope. The first edition of the great Chinese Encyclopædia, published in one hundred volumes in 1322, contains observations of forty-five sun-spots made between A. D. 301 and 1205. In spite of our meagre indebtedness to China in the field of scientific research, there is no reason to doubt the authenticity of these observations, as the largest spots are easily visible to the naked eye when the brightness of the sun's disk is reduced by smoke or haze. It is strange, however, that their existence was not recognized in Europe.

It is also an odd coincidence, though certainly nothing more, that the phenomenon of magnetism, now known to be an invariable attribute of sun-spots, is said by many authorities to have been first recognized in China. In the second century B. C. a Chinese author wrote of "magnetic cars," which he claims were given more than nine hundred years before by the Emperor to the ambassadors from Tonkin and Cochin China, to guide them on their return journey across the desert. These contained a natural lodestone, floated on water, which pointed toward

the south According to this version, the magnetic compass, used also in China for the orientation of temples, was subsequently adopted by Chinese navigators, from whom its use spread to India and thence to the Mediterranean

Whatever the facts—for the ancient Chinese made no scientific study of the sun or of magnets—our knowledge of the nature of sun-spots may be said to begin with the observations of Galileo and his contemporaries in 1610, while the optical discovery that rendered possible the detection of their magnetic phenomena was not made until 1896

HOW TO OBSERVE SUN-SPOTS

A very small telescope, or even an ordinary field-glass or opera-glass, will afford the reader a view of sun-spots at a time of solar activity. The safest way to observe them is to point the instrument at the sun and focus the eye-piece until a sharp image of its disk, several inches in diameter, is projected on a surface of smooth white cardboard held at a distance of from two to four feet Fig 33 shows how this was done by Scheiner, a contemporary of Galileo The spots can easily be distinguished from specks on the eye-piece by noticing that they move with the sun's image At present we are just emerging from a period of solar calm, during which no spots have been seen for weeks at a time But a new cycle of activity has already begun, and a few spots are beginning to appear The reader hardly needs to be warned that if he wishes to look directly

at the sun with his telescope, field-glass, or opera-glass he must protect his eyes with the blackest of smoked glass, as the intensely bright image would otherwise seriously injure them.

However, the modern astronomer makes most of his observations on photographs, and the reader

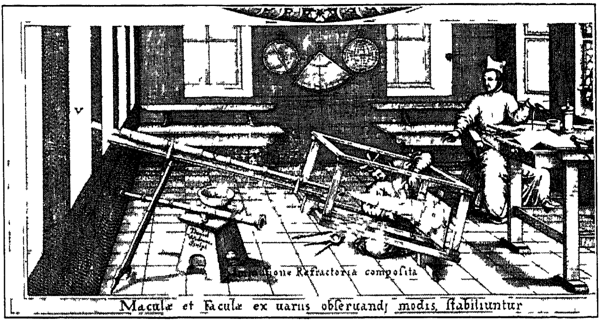


Fig 33 Small telescope used by Scheiner

This illustration, copied from Scheiner's "Rosa Ursina," published in 1630, shows how sun-spots may be observed by projecting the solar image on a smooth white surface

may enjoy the same privilege Fig 36 is a picture of the sun taken on Mount Wilson July 30, 1906, when two sun-spots were visible On the following day these spots had changed in appearance and shifted their position on the disk. This shift in position is due to the sun's rotation on its axis, easily seen by observing the spots from day to day. Sometimes they form on the visible disk, and in other cases they are first detected, surrounded by bright regions called faculæ, at the east edge (or limb) of

the sun, where they are brought into view by its rotation.

In the present chapter the strange law of the solar rotation cannot be discussed, but it may be mentioned that the sun does not rotate like a solid body, all parts of which move together. A spot near the equator completes a rotation (if it exists so long) in about twenty-five days, while one at 45° latitude takes about two and one-half days longer to return to the central meridian. Nearer the poles the rotation period is still longer.

Mention has already been made of the fact that spots are not always equally numerous on the sun's disk. In 1913, as in 1923, there were very few spots visible, and the interval between these times of minimum solar activity is on the average about 11.1 years. If we plot a curve showing the number or total area of spots on the sun, we find the large fluctuations indicated in Fig. 34. The year 1917 was one of great activity, when many spots could be seen daily. In 1923 weeks sometimes elapsed without the appearance of a single spot.

These cycles of spottedness have another peculiarity. After a minimum, the first spots of a new cycle appear in high latitudes, occasionally as great as 45°. As the cycle progresses, and the spots increase in number, their average latitude steadily decreases, so that the few that appear near the minimum are all within about 15° of the equator. Thus the advent of spots at latitudes between 30° and 40°, which occurs before the low-latitude spots of

the old cycle completely disappear, is always taken as a mark of the beginning of a new cycle The steady contraction of these sun-spot zones in the course of the cycle is also shown by Fig 34

THE STRUCTURE OF SUN-SPOTS

If our telescope is large enough we can magnify the solar image sufficiently to give us a view of the structure of sun-spots Fig 35 is from a drawing by Langley, showing the exquisite details visible with a large telescope under the best atmospheric conditions The enormous scale of the spot is suggested by the figure of the earth at the left We thus realize that when speaking of solar storms we are referring to phenomena incomparably greater and more violent than anything experienced in our own atmosphere

Terrestrial storms, whether widely extended cyclones, with moderate wind velocities, or the much smaller but far more destructive hurricanes or tornadoes, are in general whirling storms, in which the air blows along spiral lines toward a centre Seen by an observer looking down on them from above, the wind currents would invariably indicate a left-handed whirl in the northern hemisphere and a right-handed whirl in the southern hemisphere. The sun differs fundamentally from the earth in many respects, including its gaseous nature and its enormously high temperature, which shows no such difference between equator and poles as we see on the earth But the terrestrial law of storms whets our

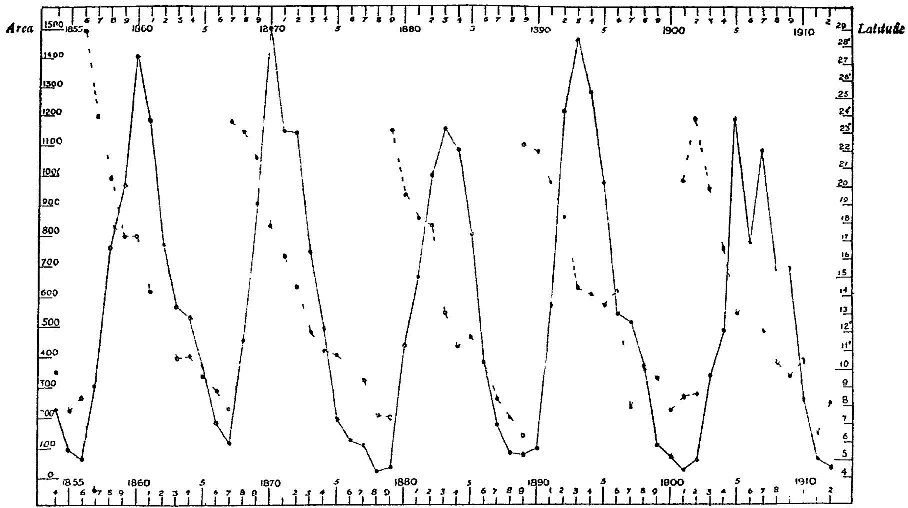


Fig 34 The periodic variation in the total area and mean latitude of sun-spots.

The continuous line represents the total area of spottedness, derived by Maunder from the Greenwich photographs The broken line giving the mean latitude of the spots for the different years, shows how each new cycle of solar activity begins in high latitudes during the minimum (From "Monthly Notices of the Royal Astronomical Society")

curiosity as to the nature of solar storms and encourages us to seek for some definite law on the sun.

Sir John Herschel was perhaps the first astronomer to suggest that sun-spots may be vast whirling storms, analogous to terrestrial cyclones or tornadoes In this belief he was later supported by the French astronomer Faye, but the observational evidence seemed to be against them The great majority of sun-spots showed no indication of vortex structure, and when the presence of curved penumbral filaments occasionally suggested it, opposite curvatures in the same spot seemed to preclude the idea that a single great vortex was at the bottom of the disturbance. The result was that the most experienced observers could see no rational grounds for the vortex theory

THE SPECTROHELIOGRAPH

In 1892, at the Kenwood Observatory, in Chicago, a new instrument was developed and thrown into the attack. This was the spectroheliograph, which will be described in its various forms in a future article. Suffice it here to say that the purpose of the spectroheliograph is to give monochromatic pictures of the sun, in the light of a single gaseous constituent of the solar atmosphere Thus a photograph taken with one of the two prominent calcium lines, H and K, at the violet extremity of the solar spectrum, reveals the immense luminous clouds of calcium vapor shown in Fig 37. These are quite invisible to the eye, as we may see by comparing this image with

that in Fig 36, which is a photograph taken at nearly the same time in the ordinary way, without a spectroheliograph The application of this new method, which makes possible the study of the solar atmosphere above and around sun-spots, might be expected to disclose the existence of definite currents or winds which would help to solve our problem.

But although the spectroheliograph was systematically applied, and improved in various ways so as to permit horizontal cross-sections of the calcium clouds at various levels to be photographed, some years elapsed before much new information was gained as to the nature of sun-spots. Then hydrogen light, the use of which involves greater technical difficulties, was employed to disclose the hydrogen clouds at various levels New and remarkable phenomena were discovered, but no clew to the enigma was found until the strong hydrogen line at the red end of the solar spectrum, known as H*a*, was tried on Mount Wilson in 1908, when plates sufficiently sensitive to red light became available This at once revealed another state of affairs, which prevails several thousand miles above the level seen in visual observations of sun-spots

Fig 39 tells no uncertain tale. It points unmistakably to the presence of two great vortices, whirling in opposite directions on opposite sides of the solar equator, and centering over two large sun-spots These spots, as seen by the eye, were in nowise peculiar, and gave no more evidence of vortex structure than others before them But the char-

acteristic forms of the hydrogen images, repeated, in varying detail, day after day, was an index that could not be ignored.

Thus without pausing to puzzle over difficult questions of secondary importance, such as the exact relationship of the high-level hydrogen structure to the spot below it, the vortex theory of spots was revived and another attack begun along a line suggested by new discoveries in physics

ELECTRONS

The first conception of definite atomic charges of electricity was reached by Faraday in his electrochemical researches It resulted from the fact that when a current is passed through a liquid a certain quantity of electricity moves from one pole to the other in association with a definite quantity of matter The elementary charges visualized by Maxwell as "molecules of electricity," and called by Johnstone Stoney "electrons" when in the form of ultimate minimum units, are now recognized as common to all matter

This began to appear in 1872, when Sir William Crookes announced the discovery of "a fourth state of matter" When the present writer lectured at the Royal Institution in 1909 on "Solar Vortices and Magnetic Fields," Sir William was kind enough to exhibit once more the very tube in which he had first shown this "fourth state of matter" in the same lecture-room many years before Following in the wake of Faraday and others, he had pumped out the

gas from the tube until only one-millionth of the original quantity was left. Through this he passed an electric discharge, appearing like a bundle of luminous rays, which he proved to consist of minute particles projected from the cathode or negative pole. These can be deviated from their straight path by a magnet and also by an electric field. They are thus shown to carry an electric charge, which Sir J. J. Thomson subsequently demonstrated to be that of the "corpuscle," or electron, which has a mass about one two-thousandth part of the mass of the hydrogen atom. The beautiful "oil-drop" experiment, by which Millikan measured the charge of these elementary units with unequalled precision, was one of the chief factors in determining the recent award to him of the Nobel prize in physics.

The experiments of Thomson and others soon proved that these negative electrons, associated in various numbers with positively charged particles of greater mass, not only constitute the atoms of all the elements but also are set free by high temperatures. They are present, for example, in all flames, and are emitted by highly heated solids and vapors. Thus they must exist in such bodies as the sun, where the temperature at the surface is more than 6000° centigrade.

It is well known that by passing an electric current through a coil of wire a magnetic field is produced. We perform this experiment every time we touch a button to ring an electric bell. An electric current is now recognized to be merely a stream of

electrons, and in a celebrated experiment Rowland produced a magnetic field by rapidly rotating an electrically charged plate Thus the whirling of the electrically charged particles undoubtedly present in a sun-spot vortex should produce a magnetic field

Fig 35 Langley's drawing of the sun-spot of March 5, 1873 (From "The New Astronomy")

The scale is indicated by the figure of the earth in the upper left-hand corner

If for any reason there were a sufficient preponderance of positive or negative charges (equal charges of opposite sign would merely counteract one another without producing a magnetic effect), the magnetic field in the sun-spot vortex might be of considerable intensity But how could it be detected at the distance of the earth ?

This was the process of "guessing by hypothesis,"

to use an expression of Faraday's, employed to guide the tests made on Mount Wilson to determine the nature of sun-spots It fortunately happened that while the spectroheliograph was being applied at the Kenwood, Yerkes, and Mount Wilson observatories, another long series of experiments had made possible the photography of the spectra of sun-spots on a large scale In these photographs certain double lines appeared, which had been seen by visual observers of sun-spot spectra and designated as "reversals," supposed to result from the superposition of vapors of different temperatures These "reversed" lines were accompanied, however, by a great number of widened lines, and this combination suggested, because of a discovery made by the Dutch physicist Zeeman, that the observed effects might in fact be due to the influence of the magnetic field called for by the vortex hypothesis. Before describing Zeeman's work, we may glance back at the earlier researches of Faraday, who was the first to detect the effect of a magnetic field on light

MAGNETISM AND LIGHT

The archives of the Royal Institution, which was founded in 1799 by the American Count Rumford, are rich beyond comparison in fundamental contributions to progress Here in long and illustrious succession such leaders as Young, Davy, and Faraday have pushed forward the boundaries of knowledge and laid the foundations of modern science and

industry No documents in the history of civilization are more interesting than the original records of great scientific discoveries, found in extraordi-

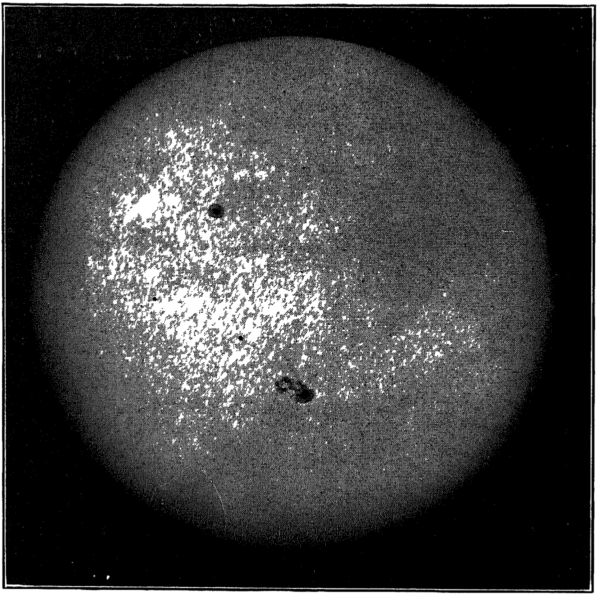


Fig 36 Direct photograph of the sun, July 30, 1906 (Palmer)

This was taken just before the calcium clouds in Fig 37 were photographed, and shows the sun-spots lying below them

nary profusion in Faraday's note-books Page after page discloses the essential germ of some prolific principle, such as the production of an electric current by moving a magnet near a coil of wire—the principle of the dynamo and the chief basis of mod-

ern electrical engineering. Such a discovery is so fundamental and so wide-spreading that it gives rise to innumerable ramifications, reaching into many fields of science and many aspects of life. In this chapter we can do no more than trace one of the ramifications of Faraday's great discovery of the effect of magnetism on light.

It came at the end of an exhaustive series of experiments, based upon a principle to which Faraday adhered with such tenacity that no discouragement could shake his faith in it.

"I have long held an opinion, almost amounting to certainty, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin, or, in other words, are so directly related and mutually dependent that they are convertible, as it were, one into another, and possess equivalents of power in their action."

Following this principle, which also guided him in many other researches, Faraday set up a powerful electromagnet, and endeavored to find evidence of the influence of its field on a beam of light passing near the poles. The light of an Argand lamp was polarized, or caused to vibrate in a single plane, by reflecting it from a surface of glass. After traversing the magnetic field it was examined through a Nicol prism, which permitted the plane of its vibrations to be determined.

Experiment after experiment ended in failure, showing no effect of the magnet, whatever the direc-

tion of the light with respect to its poles, or whatever the medium—air, many kinds of glass, Iceland spar, etc.—through which it was transmitted

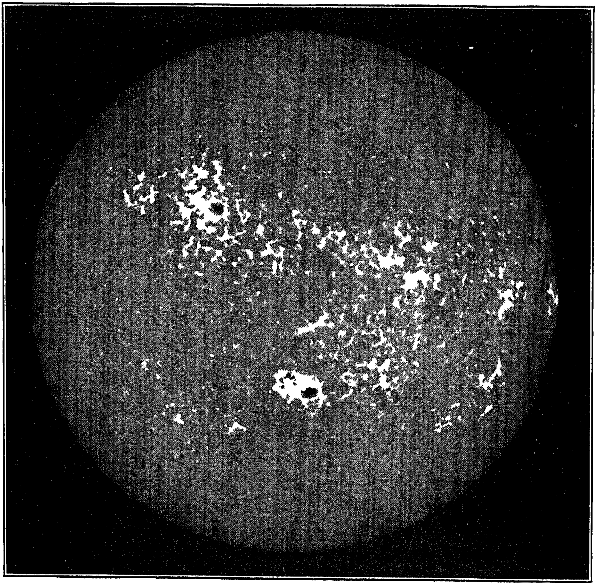


Fig. 37. Luminous clouds of calcium vapor in the solar atmosphere (Palmer)

Photographed with the 5-foot spectroheliograph of the Mount Wilson Observatory, July 30, 1906

Finally, when success seemed hopeless, the effect of some very heavy lead glass, made by Faraday many years previously in the course of certain optical experiments, was tried. The results may be given

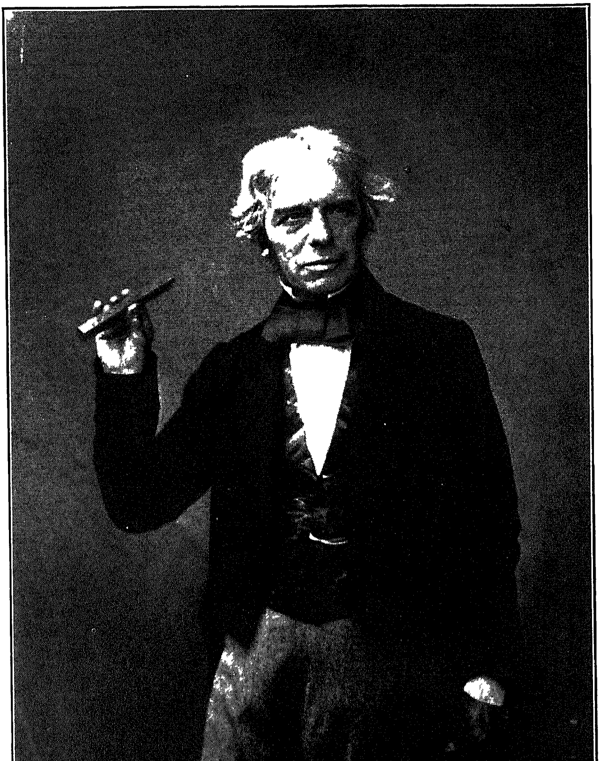


Fig 38 Michael Faraday in 1857, showing the heavy glass with which he discovered the action of magnetism on light

in his own words, copied from his original notebook:

"A piece of heavy glass (7485) which was 12 inches by 1 8 inches and 0 5 of an inch thick, being a silico borate of lead and polished on the two shortest edges, was experimented with It gave no effects when the *same magnetic poles* or the *contrary* poles were on opposite sides (as respects the course of the polarized ray).—nor when the same poles were on the same side either with the constant or intermitting current—BUT when contrary magnetic poles were on the same side there *was an effect produced on the polarized ray* and thus magnetic force and light were proved to have relation to each other This fact will most likely prove exceedingly fertile, and of great value in the investigation of conditions of natural force"

The effect thus produced was a rotation of the plane of polarization of the light, through an angle (measured by rotating the Nicol until the enfeebled light was restored to its former brilliancy) which increased with the length of the block of glass and the strength of the magnetic field. By reversing the direction of the current through the coils of the magnet, the direction of rotation of the polarized beam was also reversed. Subsequently it was found that this power of rotation was exhibited by many substances besides the heavy glass, including various liquids and also flint and crown glasses unsuccessfully tried in the first experiments.

RADIATION IN A MAGNETIC FIELD

This initial success, which had many important consequences, was obtained on September 13, 1845 On March 12, 1862, the last experiment recorded in Faraday's note-book shows how clearly he was still looking toward further possibilities. He had shown that a magnetic field can rotate a beam of polarized light passing through it from a luminous source outside of its influence But could such a field affect the nature of the light emitted by luminous particles vibrating within it?—a very different problem

Guided by the same unerring vision that astonishes us in every phase of Faraday's experimental researches, he placed sodium and lithium salts in a flame between the poles of a magnet and examined the lines of their spectra with the aid of polarizing apparatus No effect was observed, however the experiment was varied. But the instinct of the great physicist was not at fault For in 1896 Zeeman, of Leyden, aided by much more powerful apparatus, found that an intense magnetic field greatly affects the spectral lines of luminous vapors radiating within it The influence of the field, missed by Faraday merely because his instruments were too feeble to show it, is such as to resolve lines normally single into from three to twenty-one components

Zeeman's magnificent discovery, which now greatly aids the physicist in his interpretation of the nature of atoms and the constitution of matter,

was stimulated by reading Faraday's notes on his last unsuccessful experiment, as quoted by Maxwell in his "Collected Works" Zeeman was fortunately able to use a Rowland concave grating spectroscope, far more powerful than Faraday's instrument Between the poles of his Ruhmkorff magnet, also much superior to Faraday's, he placed the middle part of the flame of a Bunsen burner The experiment is best described in his own words

"A piece of asbestos soaked with common salt was put in the flame in such a manner that the D lines were seen as narrow and sharply defined lines on the dark ground The distance between the poles was about 7 millimetres If the current was put on, the two D lines were distinctly widened When the current was cut off they returned to their original condition The appearance and disappearance of the widening was simultaneous with the making and breaking of the current"

According to the theory of Lorentz, the electrons whose vibrations give rise to the D lines should experience forces which not only cause the lines to widen but actually split them up into several distinct components Moreover, these components should be polarized in distinctive ways, permitting them to be extinguished or transmitted by a Nicol prism mounted before the slit of the spectroscope, in some cases in conjunction with a mica plate or Fresnel rhomb Guided by this theory, Zeeman was able to break up spectral lines into several com-

ponents and to obliterate these at will with his polarizing apparatus.

THE TEST APPLIED TO SUN-SPOTS

Thanks to this discovery, and to the recent completion on Mount Wilson of the 60-foot tower telescope, the means for testing the vortex hypothesis of electromagnetic fields in sun-spots lay ready at hand. This instrument forms an image of the sun about 6.7 inches in diameter in a laboratory at the base of the tower, beneath which a grating spectroscope, 30 feet in length, is mounted in a well. By bringing the image of a sun-spot upon the narrow slit of the spectroscope, and holding it there by the driving-clock of the cœlostat at the summit of the tower, the thousands of lines in its spectrum can be studied either visually or photographically. As already remarked, most of these lines were already known to be widened and a few had been found to be double or triple. But such peculiarities can be caused in various ways that have nothing to do with a magnetic field. A searching test must therefore be applied, which would settle the question beyond the possibility of a doubt.

Fortunately, the unique characteristics of the Zeeman effect can be identified with complete certainty if the magnetic field that produces them is strong enough. Iron lines in the laboratory, when the luminous vapor emitting them is acted on by a magnet, are split into three or more components, polarized in distinctive ways which vary with the

angle between the direction of observation and the direction of the magnetic field. Without going into the complex details of the polarization phenomena, we may say in general that under such conditions

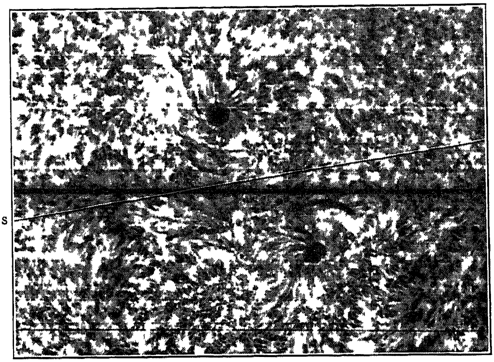


Fig 39 Right and left handed hydrogen vortices, on opposite sides of the solar equator (Ellerman)

The hydrogen atmosphere above sun-spots, photographed with the spectroheliograph at Mount Wilson on October 7, 1908 These spots were found to be of opposite magnetic polarity

as we should expect when a spot is near the middle of the sun, the central component of triple lines in its spectrum, if produced by a magnetic field, should be plane-polarized and the two outer components elliptically polarized in opposite directions Both in the number of its components and in the character of the polarization phenomena, each iron line in the spot must match its counterpart in the laboratory Moreover, all of the other elements present in the spot—sodium, calcium, chromium, titanium,

manganese, nickel, cobalt, etc.—must be no less consistent than iron, each line of each element must behave precisely as it does under similar conditions in the laboratory.

No time was lost in making the test, as the special apparatus required for the study of the Zeeman effect, including Nicol prisms, a Fresnel rhomb, and a large magnet for laboratory investigations, were available to supplement the tower telescope and its spectrograph. Two iron lines in the red part of the sun-spot spectrum, both of which were greatly widened, while one appeared to be a triplet, were first examined. The first day's observations were inconclusive. But on the second day, in the third order spectrum, definite results were obtained. A Nicol prism and Fresnel rhomb were mounted above the slit. When the Nicol was set at a certain angle, the red component of the triplet was cut off, the violet one remaining. By turning the Nicol 90°, the violet component was cut off and the red component reappeared. Other lines gave similar effects, and all of the widened lines were affected precisely as in Zeeman's original experiment. When observed with the large magnet in the laboratory, each line behaved as it did in the sun. It soon became certain, after many searching trials, that magnetic fields existed in all sun-spots examined.

WHIRLS AND COUNTER-WHIRLS

Limitations of space preclude a description in the present chapter of our studies on the nature of

the sun-spot vortex We must fix our attention here on a single application of the magnetic method, which has given a partial answer to our question regarding a possible analogy between the laws of terrestrial and solar storms.

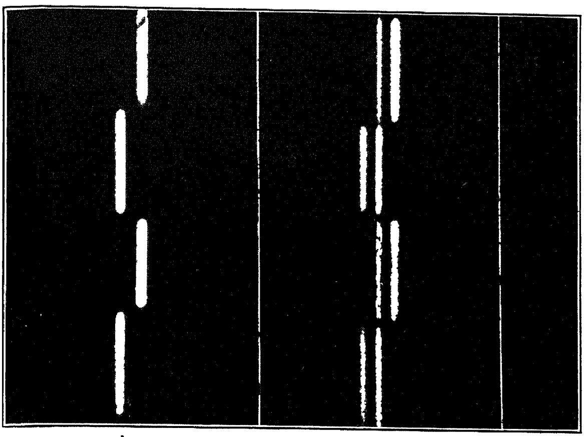
Fig. 39, showing two solar vortices whirling in opposite directions on opposite sides of the sun's equator, is temptingly like the terrestrial case The opportune appearance of these spots seemed to offer the means for a crucial test of the electromagnetic vortex hypothesis, which was immediately applied. They also prepared the way for a long investigation which has finally given us a law of sun-spot polarities.

Fig. 40 (A) represents a zinc triplet, observed in the laboratory along the lines of force, through a hole in one of the pole pieces of the magnet In this case the central component of a triplet completely disappears, and either of the side components can be extinguished at will with a Nicol prism and quarter-wave plate In a sun-spot the central component is almost always present, because we cannot often look exactly along the lines of force, and usually get an effect like Fig 40 (B), which shows the zinc triplet as seen at an angle of 60° with the lines of force But either of the side components can be extinguished, just as in the laboratory

Returning to the test with the magnet, and assuming that only one component of the triplet is visible, let us observe the effect of reversing the direction of the current flowing through the coils

The instant the current is reversed the component previously visible disappears and the other component comes into view

The same thing occurred in the two sun-spots With the polarizing apparatus unchanged their spec-



A B

Fig 40 A zinc triplet, photographed in the laboratory, (A) along the lines of force and (B) at 60° with the lines of force In both cases the side components to red and violet are transmitted by alternate strips of the compound quarter-wave mica plate, used with Nicol prism before the slit of the spectrograph (Nicholson)

tra were photographed in immediate succession The right component of the iron line appeared alone in one spot, the left component in the other Assuming the spot vortices to be whirling in opposite directions, like the hydrogen vortices above them, our

electromagnetic hypothesis supposes that charged particles are whirling clockwise in one spot, counter-clockwise in the other The coils of the magnet, into which we look just as we look into the vortex coils of the spot, carry the streaming electrons of the current When we reverse the current we cause them to flow in the opposite direction Thus the presence of one or the other component of the iron line, to the red or violet as the case may be, provides a quick and decisive index to the polarity of the spot.

It is true that we cannot yet tell with certainty the sign of the electric charge in the spot vortex, whether positive or negative Until this is learned we cannot say whether the spot vortex whirls clockwise or counter-clockwise * But we can say that two spots showing opposite components of the iron triplet are of opposite polarity, and we can also identify the polarity of each, fixing it as a north-seeking pole or a south-seeking pole A study of the magnetic observations of a large number of spots may thus lead to a law of sun-spot polarities

BIPOLAR SUN-SPOTS

As already remarked, such photographs as that reproduced in Fig 39 at first tempted us to believe that the law of sun-spot vortices is the same as that

* The hydrogen vortices shown in Fig 39 represent a higher level in the solar atmosphere and do not necessarily whirl in the same direction as the low-lying spot vortices The nature of the hydrogen vortices and their relationship to the spots below them will be discussed in a future article on the remarkable phenomena of the solar atmosphere

of our cyclones and tornadoes, which whirl clockwise in one hemisphere, counter-clockwise in the other We soon found, however, that spots of opposite polarity, presumably representing vortices whirling in opposite directions, occur in the same hemisphere of the sun This complicated the problem, but a decisive discovery then prepared the way for an effective attack

In the earliest drawings of Galileo and Scheiner, and in those of all subsequent observers, we find many spot groups depicted as pairs, or as long streams of spots lying nearly parallel to the solar equator. The spot drawn by Langley (Fig. 35) is one of this type. Magnetic observations of such groups showed us that in almost every case the spots of a pair, or the clusters of spots lying at opposite ends of a stream, are of opposite polarity. Occasionally, it is true, the spots of these groups are so mixed that no sign of order can be detected. But some 60 per cent of all spots may be classified without hesitation as definite bipolar groups

Of the remaining single spots, or closely clustered groups of spots of the same polarity, about 30 per cent are either preceded or followed by a train of faculæ or flocculi, in which a second spot, of opposite polarity, sometimes appears intermittently This peculiarity led to a search for invisible spots, which have been detected in the following way:

We conceive of a sun-spot on the vortex hypothesis as a region in which the luminous gases, cooled by the expansion caused by centrifugal action, ap-

pear as a darkened cloud upon the brilliant photosphere Proof of this cooling is given by spectroscopic observations, which show changes in the relative intensities of lines due to reduced temperature and also the presence of such compounds as titanium oxide and magnesium hydride, the constituents of which occur uncombined in the hotter parts of the sun's atmosphere It is easy to imagine the existence of vortices in which the cooling due to expansion is insufficient to produce a perceptible darkening of the photosphere Such vortices may nevertheless give rise to magnetic fields detectible by the Zeeman effect.

On account of the weakness of the field in small vortices, their existence can be disclosed only by an extremely small widening of certain lines in the spot spectrum A minute moving object is more easily seen than a fixed one, so the slight widening is caused to appear alternately on each side of the line by means of a special polarizing device oscillating back and forth across the slit of the spectroscope In this way weak magnetic fields have been found in masses of faculæ, usually preceding or following single spots Sometimes these incipient spots, after observation in their invisible state for two or three days, have become visible, only to disappear later, when their presence as vortices has again been detected by their magnetic effect Thus we now have a means of studying sun-spots in their embryonic and post-mortem states

The discovery of invisible spots strengthens our

system of classification, which treats single spots as the preceding or following members of incomplete bipolar groups. The disposition of the calcium flocculi behind or in front of the spot, as revealed by the spectroheliograph, determines the classification.

THE DAILY POLARITY RECORD

Prior to the sun-spot minimum of 1913 our attention was chiefly concentrated on a few of the largest spots, in which the various complex manifestations of the Zeeman effect were studied. With the 60-foot tower telescope and 30-foot spectrograph then in use the smaller spots were beyond the range of observation, and no extensive investigation of polarities was undertaken. The success of this telescope, the first of its kind, led us to design and build a much more powerful instrument of the same type, with which the polarities of all spots on the sun are recorded daily.

The familiar equatorial telescope, with its moving tube, is limited in length and unable to carry the very long spectroscopes needed for solar research. A series of investigations, beginning at the Kenwood Observatory in 1891 and continued with the forty-inch refractor of the Yerkes Observatory, led to the construction of the Snow horizontal telescope, with which the vortices in the solar atmosphere were discovered, and subsequently to the development of telescopes of the tower type.

The 150-foot tower telescope, completed in 1912, consists of a cœlostat and second mirror at the sum-

mit of a tower, which receive the sunlight and reflect it vertically downward to a 12-inch objective of 150 feet focal length, mounted just below them This forms an image of the sun about 16½ inches in diameter in a laboratory at the foot of the tower Any

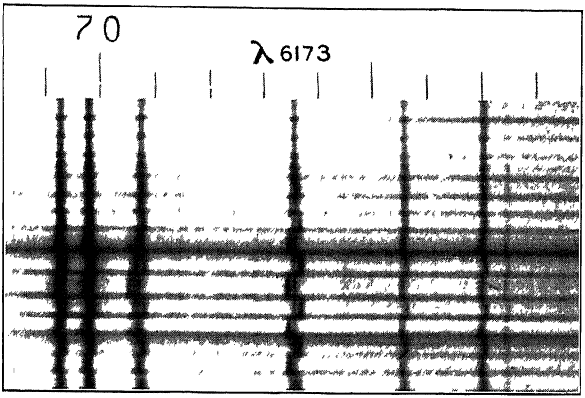


Fig 41 The Zeeman triplet λ6173 in the sun-spot spectrum (Ellerman)

Photographed in the second order spectrum of the 75-foot spectrograph of the 150-foot tower telescope The polarity of the spot is determined by the transmission of the red or violet component of the triplet by the "marked strip" of the compound quarter-wave plate

part of this large image, such as a small sun-spot, can be held indefinitely on the slit of a powerful spectrograph 75 feet in length Through the slit its light descends into a well about 80 feet deep, excavated in the rock beneath the tower Near the bottom of the well, after being rendered parallel by a six-inch lens, the rays fall upon a plane surface of

polished speculum metal, ruled by a diamond point with lines at the rate of about 14,000 to the inch This grating decomposes the white light into its constituent parts and sends it back through the lens, which forms an image of the resulting spectrum near the slit in the room at the base of the tower. So great is the dispersion that the light which descends through a slit only three thousandths of an inch wide is returned as a spectrum about 40 feet long, from red to violet This is the spectrum of the second order, in which the polarity observations are made Fig 41 shows the iron triplet $\lambda 6173$, as photographed in a sun-spot with this spectrograph Observations of this line in all sun-spots give a daily record of their polarity and field strength

THE LAW OF SUN-SPOT POLARITIES

Sun-spots were on the wane from the beginning of this work in 1908 until the minimum of solar activity in 1913 During this period only 26 spot groups were observed magnetically, but these sufficed to reveal the polarities then characteristic of the northern and southern hemispheres With but two exceptions, all of these groups showed that preceding spots in the northern hemisphere were of south polarity (with south-seeking poles), while their following spots were of north polarity In the southern hemisphere the order was reversed—preceding spots were of north, following spots of south, polarity.

This rule persisted in 1912, when the few spots at

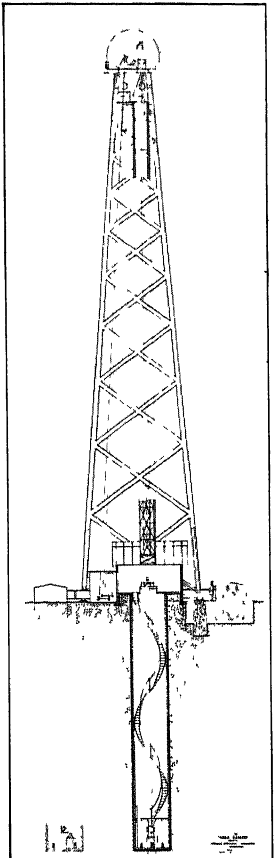


Fig 42 The 150-foot tower telescope of the Mount Wilson Observatory

A spectrograph of 75 feet focal length, mounted in a well beneath the base of the tower, is used daily to determine the magnetic polarity and field strength of all sun spots seen on the 16 5 inch solar image

the end of the old cycle, in harmony with the ordinary law, were still appearing at infrequent intervals near the equator The first small spots of the next eleven-year cycle then began to break out in high latitudes, and to our surprise their polarities were found to be reversed Since that time, with the superior advantages afforded by the 150-foot tower telescope, the magnetic fields of 2,110 spot groups of this cycle have been observed, chiefly by Ellerman, Nicholson, Joy, and Pettit. After excluding the small number of spots that cannot be classified we find that all of these groups, with only 4 per cent of exceptions, follow this new rule preceding spots in the northern hemisphere have north polarity, while preceding spots in the southern hemisphere have south polarity Some extraordinary change had occurred in the

sun, which on the most plausible interpretation could mean nothing less than a reversal in the direction of whirl in sun-spot vortices.

Under these circumstances we naturally looked forward with keen interest to the next sun-spot minimum, which has now arrived. As the cycle progressed the average latitude of the spots steadily decreased, finally bringing us back to conditions resembling those of 1912, with small and infrequent spots appearing near the equator Spots announcing a new cycle sometimes develop as much as two years before the minimum, and in this case the first one was found by Ellerman on June 24, 1922, at 31° north latitude It was a small single spot, but seemed to be a preceding one, and its observed polarity was south, corresponding to that of preceding spots in the northern hemisphere during the cycle ending in 1913 Another reversal of polarity was thus foreshadowed

Since that time a number of spots of the new cycle, including some fine bipolar groups, have developed in high latitudes, while the low-latitude spots have practically ceased to appear The new spots completely confirm the expected magnetic reversal, and give us the polarity law expressed graphically in Fig 43 As the curves indicate, the polarities of the great majority of spots, opposite in the northern and southern hemispheres, remain the same throughout the eleven-year period and suddenly reverse with the renewal of activity in high latitudes Thus the spots of alternate cycles are alike magnetically, and a period of about twenty-

two years elapses between the successive appearances of similar spots In one sense this may be regarded as the true sun-spot period, as it is the interval between successive returns of the sun to the same state But the old period of about eleven

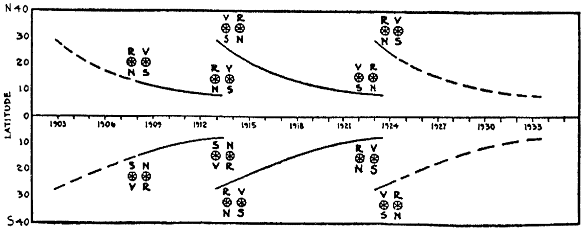


Fig 43 The law of sun-spot polarity

The curves show the approximate variation in mean latitude and the corresponding magnetic polarities of 2,110 sun-spots observed at Mount Wilson from 1908 to 1923

years correctly represents the fluctuation in number and area of all spots, counted without regard to their magnetic character

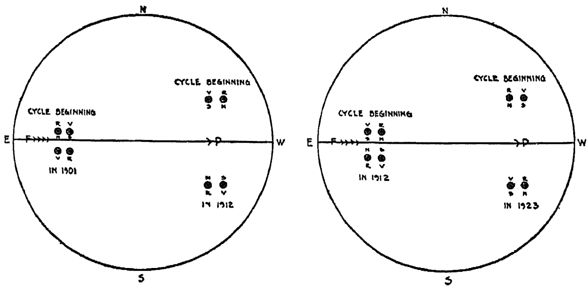
The conditions existing at successive minima, when two spot zones of opposite polarity coexist in each hemisphere for about two years, are shown in Fig 44. There seems to be no terrestrial analogue for the combination of right and left handed vortices in pairs, as in bipolar spots, for the temporary occurrence in each hemisphere of two storm zones characterized by opposite directions of whirl, such as we see in Fig 44, or for the gradual descent in latitude and the periodic reversal in the direction of whirl illustrated in Fig 43

TERRESTRIAL AND SOLAR STORMS

But why, it may be asked, may we not regard the vortices of bipolar spots as whirling in the same direction, and account for their opposite polarity by supposing the dominant electric charges in each to be of opposite sign? We do not yet fully understand the mechanism of the process that separates the positively and negatively charged particles in the sun and causes one or the other to dominate in a spot vortex. In thunder-storms, as Simpson has shown, the separation of electricity is probably due to the violent disruption of rain-drops or the collision of hail with snowflakes. As the conductivity of the atmosphere is low, the wide separation of electricity necessary to give a lightning flash is possible. The conditions are very different on the sun, because of the high temperature and conductivity of the gaseous atmosphere, and we certainly have no evidence that the charges in the two spots of a bipolar group are of opposite sign. If such could be the case, it would be difficult to show how this sign could depend upon the hemisphere, the latitude, or the spot cycle, not to speak of other objections Difficult as the hydrodynamical problem involved in the alternative view may appear, it seems far easier to suppose that the dominant charge is the same in all solar vortices and that the polarity is determined by the direction of whirl

But why should this vary in the remarkable way indicated by our observations? Even the associa-

tion in pairs of vortices whirling in opposite directions is not easy to explain, though both theory and experiment agree in showing that a columnar vortex, extending deep into the sun, may turn up to the surface to form a half-ring vortex This might



Minimum of 1913 Minimum of 1923

Fig 44 Sun-spot zones during the minimum of solar activity

Two zones in each hemisphere, in which the spots are of opposite polarity, co-exist for about two years at the time of each sun-spot minimum

account for some very simple bipolar spots, but many complex groups seem beyond the range of this attractive hypothesis The periodic reversal of the direction of whirl, which evidently depends upon the ebb and flow of solar activity that marks the sun-spot cycle, remains as the crucial problem The very nature of the sun itself seems to be involved, and with it, perhaps, the nature of other dwarf stars

The traditional explanation of the direction of whirl in terrestrial cyclones, which dates from an early period, is a very simple one. Suppose a re-

gion of low pressure to occur at some point in the northern hemisphere The wind rushing toward the depression from the south carries with it the higher moment of inertia of the atmosphere, in the equatorial region, and its velocity must increase and deflect the air to the east of the meridian from which it started The air descending from the north acquires a lower velocity and is deflected to the west Hence the left-handed whirl In the southern hemisphere, as a moment's reflection will show, a right-handed whirl would be produced under similar conditions

This explanation has been questioned in recent years, and it certainly does not suffice to account for the vortices that cause magnetic fields in sun-spots We now find (though the investigation is still far from complete) that the direction of whirl of the inflowing vortices shown by the spectroheliograph in the hydrogen atmosphere above sun-spots apparently does not depend upon the polarity of the corresponding spots or reverse in direction at sun-spot minima * Indeed, these vortices seem to be secondary phenomena, induced above spot vortices, which appear to lie at a much lower level, below the photosphere Moreover, no sign of any radical change in the circulation of the solar atmosphere, such as the reversal in the direction of whirl in spot vortices would surely involve if they were high-level

* About 75 per cent of the hydrogen vortices associated with single or preceding spots in both hemispheres conform in direction of whirl with terrestrial cyclones

phenomena, has been detected. The peculiar law of the solar rotation persists without known change through the spot minimum, and all the evidence seems to favor the view that sun-spots are deep-seated manifestations of the internal circulation of the sun. In these mysterious depths we should therefore seek for the origin of sun-spots, the nature of their characteristic cycle, and the cause of the periodic reversal of their magnetic polarity.